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MACCS Theory Manual

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ABSTRACT

This report describes the models of the MACCS computer code as presented in MACCS Version 3.10.0. The purpose of MACCS is to simulate the impact of severe accidents at nuclear power plants on the surrounding environment. MACCS has been developed by Sandia National Laboratories for the U.S. Nuclear Regulatory Commission.

From a given release of radioactive material into the atmosphere, MACCS estimates the extent and magnitude of radiological contamination, offsite doses, protective actions, socioeconomic impacts and costs, and health effects. Since the weather at the time of an accident is not predictable, MACCS supports various sampling options to run a representative set of simulations to evaluate weather variability. MACCS simulates atmospheric transport with a straight-line Gaussian plume segment model. From the estimated air and ground concentrations, MACCS models dose projections through several dose exposure pathways. These exposures can be offset by protective actions during the emergency response and long-term recovery of the accident. MACCS users directly specify the evacuation and sheltering area, while other protective actions (e.g., relocation, farmland restrictions, decontamination) are based on user-specified dose or concentration limits. While protective actions help reduce dose accumulation, they also cause social and economic impacts. MACCS models the extent of displaced individuals and land contamination, and the cost of offsite property damage, economic disruptions, and various accident expenditures caused by protective actions. Finally, from the dose accumulation, MACCS estimates early and stochastic health effects according to dose-response models.

The purpose of consequence analyses is to be able to understand and estimate the impact of nuclear accidents. Consequence analysis is an essential tool to inform determinations of adequate protection of the public, to understand nuclear power hazards, to measure the value of regulations, and to help us appreciate the importance of nuclear safety. As such, MACCS has a variety of regulatory uses including environmental analyses (10 CFR 51.53, 52.47), regulatory cost-benefit analyses, backfit analyses (10 CFR 50.109), consequence analysis studies such as SOARCA (NUREG-1935), Level 3 PRA studies, and risk-informing of emergency planning (10 CFR 50 App. E and 50.47).

This report updates the previous MACCS theory manual (NUREG/CR-4691 Vol. 2; Chanin, Sprung, Ritchie, & Jow, 1990) and accompanies the MACCS User's Guide (SAND-2021-1588) that describes the use and input requirements of the graphical user interface of MACCS known as WinMACCS. The MACCS User's Guide is also a reference guide that describes data input file formats, describes various software components in the MACCS code suite, and provides a set of example tutorials for running WinMACCS. Also, soon to be published is a MACCS input parameter guidance report (NUREG/CR-7270) that provides technical bases for commonly used MACCS input values.

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LIST OF ABBREVIATIONS

ATD	Atmospheric transport and diffusion
CCDF	Complementary cumulative distribution function
DCF	Dose conversion factor
DDREF	Dose and dose-rate effectiveness factor
DRF	Dose reduction factor
EPA	Environmental Protection Agency
HPS	Health Physics Society
HYSPLIT model	Hybrid Single-Particle Lagrangian Integrated Trajectory model
ICRP	International Commission on Radiological Protection
KI	Potassium iodide
LNT	Linear no threshold
NASA	National Aeronautics and Space Administration
NCRP	National Council on Radiation Protection & Measurements
NEPA	National Environmental Policy Act
NRC	Nuclear Regulatory Commission
P-G	Pasquill-Gifford
RBE	Relative biological effectiveness
SCRAM	Support Center for Regulatory Atmospheric Modeling
SOARCA	State-of-the-art Reactor Consequence Analyses

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1 INTRODUCTION

Sandia National Laboratories has developed a severe accident consequence assessment code, MACCS, for the U.S. Nuclear Regulatory Commission. MACCS calculates the offsite consequences of an atmospheric release of radioactive nuclides.

The Introduction (this section) discusses an overview of the major computational models, the spatial grid, population cohorts, the computational framework, and MACCS outputs. After the Introduction, the next five sections of this report describe in detail the major computational models to treat Atmospheric Transport (Section 2), Dosimetry (Section 3), Protective Actions (Section 4), Socioeconomic Impacts and Costs (Section 5), and Radiogenic Health Effects (Section 6).

Each section describes the equations and parameters of the computational models of the MACCS code. In this report, the names of the user-specified input parameters are upper case and typically six characters long. These are the names (i.e., identifiers) of the input parameters in the MACCS Fortran code. The WinMACCS user interface also has a set of names for the input parameters. The input parameter names in MACCS and WinMACCS are usually the same, but not always. Also, WinMACCS users may find that WinMACCS does not display certain MACCS parameters that affect the calculation workflow or that are used to select different modeling options. Instead, WinMACCS users control these inputs within the “Project Properties” window. The MACCS User's Guide provides more information on how to use the WinMACCS user interface.

1.1 Model Overview

MACCS models the offsite consequences of a severe reactor accident that releases a plume of radioactive materials into the atmosphere. Should such an accidental release occur, the radioactive gases and aerosols in the plume would be transported by the prevailing wind and disperse in the atmosphere. Radioactive materials deposited from the plume would contaminate the environment and expose the population to radiation. The objective of a MACCS calculation is to model the extent and magnitude of radiological contamination, offsite doses, protective actions, socioeconomic impacts and costs, and health effects that would result from a release of radioactive material into the atmosphere.

There are two fundamental aspects of the organization of MACCS, which are basic to its use. First, MACCS divides time after an accident into three phases: the early, intermediate, and long-term phases. Second, MACCS uses a grid based on a polar coordinate system to represent the region surrounding the release location.

The early phase is modeled by the ATMOS module and the EARLY module of MACCS. ATMOS models atmospheric transport during the early phase of the accident, while EARLY models the early doses and emergency response during the early phase. MACCS assumes the early phase begins at accident initiation. The start of the early phase exposure depends on the protective action models and can last up to 40 days. Models in this phase treat the exposure of the population from both plume passage and ground contamination. There are several protective action models in the early phase, including sheltering, evacuation, dose-dependent early relocation, and potassium iodide (KI) ingestion.

The intermediate phase is modeled by the CHRONC module. In the intermediate phase, MACCS assumes the plume of radioactive material has moved through and out of the grid before this phase begins and only treats exposure pathways from ground contamination. The only protective action that can be taken during this period is intermediate phase relocation. The duration of this phase can be set to zero, which allows the long-term phase and its associated protective actions to begin immediately after the early phase, or it can be set to a period of up to 30 years.

The long-term phase occurs after the intermediate phase and is also modeled by the CHRONC module of MACCS. As with the intermediate phase, ground contamination is the source of all exposure pathways. The long-term phase models protective actions, including habitation and farming restrictions (which can lead to interdiction or condemnation of property), and decontamination. The long-term phase exposure periods are more complex than those for the early and intermediate phases because they differ by exposure pathway. Assuming no restrictions, external exposures begin when the intermediate phase ends and last for a user-specified period, whereas the transport of deposited radionuclides into the food and drinking water supply begins when the early phase ends.

The spatial grid on a polar-coordinate system represents the region and is centered on the reactor itself. That is, the reactor is located at the point ($r = 0$). The number of radial divisions as well as their endpoint distances define the radial intervals of the grid. The user can specify up to 35 radial intervals extending out to a maximum distance of 9,999 km. The number of angular divisions, θ, define the directions of the compass sectors of the spatial grid. The user can define up to 64 directions in multiples. MACCS stores results based on this polar-coordinate grid.

Additionally, MACCS also defines a fine spatial grid. Starting with the regular (coarse) spatial grid, the code divides each compass sector into 3, 5, or 7 user-specified lateral subdivisions to create fine spatial elements. Because of the importance of capturing an accurate dose distribution for early health effects, MACCS uses the fine spatial elements to calculate doses in the early phase and uses the regular spatial grid for other calculations.

1.1.1 MACCS Input Data and Outputs

MACCS calculations require the following input data:

The fuel **inventory** at accident initiation (e.g., reactor scram) of those radioactive nuclides important for the calculation of offsite consequences.

The atmospheric **source term** produced by the accident. In addition to the radionuclide fuel inventory, the code requires several plume segment characteristics that define the release. These include the atmospheric release fraction, the heat content, the initial release and duration, and the initial release height and initial dispersion for each plume segment. The code also requires the distribution of aerosol sizes of the released inventory.

Meteorological data characteristic of the site region (usually one year of hourly windspeed, wind direction, atmospheric stability class, and rainfall rate recorded at the site or at a nearby National Weather Service station). Although one year of hourly readings provides 8,760 data points, which can be associated with 8,760 weather sequences starting at the beginning of each hour, MACCS can be more computationally efficient by sampling a representative subset of these sequences. To do this, MACCS can categorize weather sequences into bins defined by windspeed, atmospheric stability class, and intensity and distance of the occurrence of rain to ensure that the sampled sequences are representative of a variety of weather conditions.

A weather trial is defined as a consequence simulation using a specific weather sequence. A weather sequence is defined as a set of hourly weather data. The basic concept of a weather trial is a pairing of weather that potentially changes hour-by-hour with a source term that also changes hour-by-hour.

The **population distribution** around the reactor site. Site-specific population distributions are constructed from census data on a polar coordinate grid having up to 64 angular compass sectors and up to 35 radial intervals.

Emergency response assumptions for sheltering and evacuation (e.g., sheltering and evacuation area, sheltering and evacuation timeline, network or radial evacuation, evacuation speed, and travel distance), KI ingestion description (e.g., population fraction taking KI and the associated efficacy), and early relocation (e.g., dose criteria, relocation timing).

Long-term protective actions (e.g., decontamination, habitation restrictions, farming restrictions, and contaminated crop and milk disposal), which are often based on protective action guides.

Land usage data (e.g., habitable land fractions, farmland fractions), and **economic data** (e.g., worth of crops, land, and buildings) for the region around the reactor site.

Dosimetry information (i.e., dose coefficients) for converting air and ground concentrations into dose estimates for various exposure pathways, including cloudshine, groundshine, inhalation, and ingestion. In MACCS, dosimetry information for skin deposition is contained in the code.

Given the preceding input data, MACCS estimates the following:

- The downwind **transport**, **dispersion**, and **deposition** of the radioactive materials released into the atmosphere from the source (e.g., failed reactor containment), resulting in offsite air and ground concentrations of radioactive material.

- The early and late **radiation doses** received by exposed populations through various exposure pathways, including cloudshine, groundshine, skin deposition, inhalation, and ingestion, accounting for protective actions designed to reduce exposures.

- The **socioeconomic impacts** and **costs**, including the number of displaced individuals, the extent of land contamination, offsite property damage, economic disruptions, and certain accident expenditures such as decontamination and relocation expenses. Many socioeconomic impacts and costs result from protective actions intended to reduce public health risks.

- The **early injuries and fatalities** expected to occur within one year of the accident (i.e., early health effects) and the stochastic effects (e.g., latent **cancer incidences** and **fatalities**) expected to occur over the lifetime of the exposed individuals.

1.1.2 Atmospheric Transport

MACCS allows a release of radioactive materials into the atmosphere to be divided into successive plume segments, which can have different compositions, initial release times, durations, release heights, and energies (amounts of sensible heat). Plume segment lengths are determined by the product of the segment's release duration and the average windspeed during release. The user specifies the initial vertical and lateral dimensions of each plume segment, which can be used to account for the initial plume spread from building wake effects.

A liftoff criterion (a critical windspeed that increases with plume buoyancy [Hall & Waters, 1986]) determines whether buoyant plumes are subject to plume rise. When the windspeed at release equals or exceeds the critical windspeed, the plume centerline remains at its initial height. When the windspeed at release is less than the critical windspeed, plume rise can occur. There are two methods to calculate the buoyancy of a plume, and two models to calculate the height to which a buoyant plume rises based on equations recommended by Briggs (Briggs, 1975; Hanna, Briggs, & Hosker, 1982).

After release, windspeed determines the rates at which plume segments transport in the downwind direction. Wind direction at the time of release determines the direction of travel for the duration of the plume segment. The atmospheric transport model is a straight-line Gaussian plume segment model, and like other Gaussian models, this neglects wind trajectories.

The Gaussian plume dispersion model estimates plume expansion in the lateral and vertical directions assuming a normal distribution (Kao, 1984). The rate of plume expansion is determined by lateral and vertical dispersion parameters. There are three options for modeling this dispersion rate; two of them are distance-based and one is time-based. Although lateral dispersion of plume segments in the crosswind direction is unconstrained, vertical dispersion is bounded by the ground and by the top of the mixing layer (as specified by annual or seasonal mixing layer heights [Holzworth, 1972]), which are modeled as reflective boundaries (Kao, 1984). Eventually, the plume segments become well mixed in the vertical direction and the atmospheric transport model converts the vertical Gaussian distribution into a uniform distribution (Turner, 1970).

Aerosols are removed from the plume by radioactive decay, by wet deposition, which varies with rainfall rate (Brenk & Vogt, 1981), and by dry deposition (primarily diffusion, impaction, and gravitational settling) onto surfaces. The combined removal rate from diffusion, impaction, and settling is modeled using an empirical, dry deposition velocity (Sehmel, 1984). Because dry deposition velocity varies with particle size, the user can discretize the source term into bins according to aerosol size and provide a dry deposition velocity for each bin.

Post-atmospheric transport is only considered to the extent necessary for calculating doses through certain exposure pathways. Groundshine and resuspension inhalation consider weathering, which accounts for post-deposition environmental effects (e.g., wash off, percolation), which can reduce doses, for instance, from reduced concentrations or increased soil shielding. Groundshine weathering is modeled using Gale's equation (Gale, Miller, & Fisher, 1964), which is considered in the intermediate and long-term phase but not the early phase. Resuspension weathering is modeled in all phases and uses resuspension factors (Sehmel, 1984) that attempt to represent the average effect of resuspension by many processes at very different rates throughout large regions.

The food and drinking water exposure pathways consider a subset of the radionuclides modeled by atmospheric transport. The water ingestion pathway considers direct deposition onto the surface of water bodies that can then enter the drinking water supply, and washoff of radioactive material from land into water bodies. The food ingestion pathway considers direct deposition onto crops and soil in farm areas. There are two food-chain models available, the original MACCS food-chain model and the COMIDA2 food-chain model, both with detailed transfer mechanisms among important components of the food chain.

The ATMOS module of MACCS initially models atmospheric transport without regard for decay and ingrowth, and subsequently adjusts the resulting air and ground concentrations for radioactive decay. For the early phase, ATMOS calculates a set of air and ground concentrations for each plume segment. For the intermediate and long-term phase, MACCS sums the ground concentrations from each plume segment together and calculates decay and ingrowth so that the decay from each plume segment is consistent with the end of the early phase. After atmospheric transport, the dose equations in EARLY and CHRONC also consider radioactive decay and ingrowth as needed.

1.1.2.1 Weather Data

Plume rise, dispersion, downwind transport, and deposition depend on prevailing weather conditions (e.g., windspeed, atmospheric stability, precipitation rate). In MACCS, weather data may either be invariant or may vary hour-by-hour as defined for a weather sequence. Variable weather data either can be user specified or can be read from a weather file.

MACCS requires the user to specify the risk dominant plume segment. Usually, the risk-dominant segment is the one most capable of producing acute doses that dominate early fatalities (e.g., the blowdown puff of a three-segment release comprised of a leak, a blowdown puff, and molten-core/concrete interaction tail). Once a risk-dominant segment has been specified, MACCS automatically causes the reference point of that segment to be released at the beginning of the first hour of weather data.

1.1.3 Dosimetry

In addition to reporting doses, MACCS uses doses for two main purposes, (1) to calculate health effects from ionizing radiation (i.e., radiogenic health effects) and (2) to help determine the location of protective actions. To calculate health effects, MACCS computes three types of doses: acute doses, lifetime doses, and annual doses. MACCS uses acute doses to calculate early health effects. Depending on the dose-response model, MACCS uses either lifetime or annual doses to calculate cancer effects, as discussed in Section 6 of this report.

MACCS models the following seven exposure pathways. Early dose pathways include cloudshine, groundshine, direct inhalation, resuspension inhalation, and skin deposition. Late dose pathways include groundshine, resuspension inhalation, and food and water ingestion.

MACCS treats the first five exposure pathways as “direct” pathways, meaning that the individual residents within the affected spatial element receive these doses. The food and water ingestion pathways are “indirect” pathways, meaning that the individual residents within the spatial element where deposition occurs may not be the ultimate recipients impacted by these dose contributions.

As such, MACCS calculates population doses (*person-Sv*) from the ingestion pathways and tally these doses to the spatial element where the deposition occurs that contributes to the ingestion dose, but MACCS excludes ingestion doses from the tally of individual doses (*Sv*). MACCS also calculates groundshine doses to decontamination workers, which like ingestion, is included in societal metrics but not individual metrics. As such, societal metrics (e.g., population doses, number of health effects) that consider both direct and indirect pathways are a more complete measure of accident consequence than individual metrics that only consider direct pathways.

MACCS calculates doses using dose coefficients to convert from an activity level to a dose. Dose calculations are based on air or ground concentrations from the atmospheric transport model results. Because the atmospheric transport model calculates air and ground concentrations only along a plume segment centerline, the dose calculations use off-centerline correction factors to compute the average dose in a spatial element.

Some dose calculations in MACCS are for informing radiation protection. These dose projections act as a trigger that determine when a protective action is necessary. They assume a stationary individual as if no protective actions were to occur. However, MACCS assumes the doses people receive from the accident depend on the protective actions. Protective actions may impact the duration of exposure, the activities of the cohort that affect protection factors, and ground concentrations.

1.1.4 Protective Actions

MACCS divides time after accident initiation into three phases: an early phase, an intermediate phase, and a long-term phase. During the early phase, which can last up to forty days, doses are reduced by sheltering, evacuation, and early relocation of people. During the intermediate phase, doses may be avoided by enforcing habitation restrictions (i.e., relocation), and ground contamination would be surveyed to prepare for decontamination actions. During the long-term phase, doses are reduced by habitation restrictions, farming restrictions, and decontamination of property that is not habitable. Protective actions help reduce doses and associated health effects; however, protective actions are disruptions with societal and economic impacts.

During the early phase, MACCS assumes evacuation and sheltering automatically take place within some specified region without regard to projected exposures. Outside of this region, people in the early phase only evacuate if their projected doses exceed a user-specified dose criterion (note: MACCS calls this early “relocation”). For those inside the evacuation and sheltering region, there is a delay to the alarm time, a delay to shelter that accounts for the time before the public receives the notification and travels home to shelter (or shelters in place), and a delay to evacuate during which time sheltering occurs and people mobilize to evacuate. After these delay periods pass, MACCS models that people proceed either in a radial direction away from the reactor site or according to a network evacuation, which is a user-specified pattern on the spatial grid that can represent the actual evacuation routing. At some radial distance outside the evacuation zone, evacuees are assumed to accumulate no additional dose during the early phase.

MACCS assigns populations to three activity types at any given time: evacuation, sheltering, and normal activity. It is up to the user to specify appropriate protection factors for these activities. Users commonly specify vehicle protection factors to calculate doses to evacuees. Protection factors for people who actively take shelter are generally smaller (i.e., they are better shielded) than those for people who continue normal activities because people who actively take shelter are assumed stay inside, close doors and windows, turn off air circulation systems, and move to interior rooms or basements.

In the intermediate and long-term phases, relocation occurs only if the projected doses exceed a user-specified dose criterion. At the beginning of the long-term phase after the accident, MACCS projects the doses that people would receive if no recovery actions were taken and compares those doses to the user-specified long-term habitability criterion. If the long-term habitability criterion is not met, MACCS attempts to meet the criterion, first with escalating levels of decontamination effort and, if that is insufficient, by decontamination followed by an additional period of temporary interdiction to allow radionuclide removal by weathering and radioactive decay. However, these actions are taken only if they are cost effective (i.e., the worth of the recovered property is greater than the sum of the following recovery costs: decontamination costs, earnings from investments that are lost during temporary interdiction of property, and the cost of any repairs necessitated by lack of maintenance of property during the temporary interdiction period).

During the long-term phase, dose is also avoided by controlling the consumption and production of contaminated foodstuffs. Using the original MACCS food-chain model, food ingestion doses are broken down into growing season pathways and a long-term food ingestion pathway. When the accident occurs during the growing season, the accident may contaminate crops and pastures by direct deposition onto plant surfaces. Disposal occurs when either ground concentrations of food pathway radionuclides exceed user-specified maximum allowable ground concentrations, or when ambient doses in farm areas exceed the habitability dose criterion. In the long-term food ingestion pathway, farming is prohibited unless a similar set of criteria are met.

Using the COMIDA2 food-chain model, farming restrictions occur when the maximum food ingestion dose to an individual exceeds allowed dose levels or when ambient doses exceed habitability. Consistent with the original food-chain model, MACCS disposes of crops and milk according to one set of farmability criteria and prohibits farming in subsequent years based on an another farmability criterion when using the COMIDA2 food-chain model. Crops cannot be consumed in the first year if land is not farmable in the second year.

Farmland decontamination reduces ambient doses from groundshine and from inhalation of resuspended radioactive materials, potentially making the land farmable if restricted due to the habitability criterion. However, MACCS assumes decontamination does not decrease uptake of radioactivity by root systems and thus does not affect food ingestion doses, although in reality this can depend on the type of decontamination that is performed.[1] As such, MACCS assumes that food ingestion doses can only be decreased by temporary interdiction of farmland to allow radioactivity to be removed by weathering and decay, a procedure MACCS allows only if the length of the interdiction period does not exceed eight years.

[1] For instance, soil scraping can reduce radionuclide concentrations whereas deep plowing does not.

1.1.5 Socioeconomic Impacts and Costs

The socioeconomic impacts and costs are the set of consequences produced by a nuclear accident. This includes property damage, economic disruptions, various accident expenditures, health effects, environmental damage, and societal disruptions. In this report, radiogenic health effect modeling is discussed separately in more detail (Section 1.1.6).

The MACCS cost models consider the following losses:

- Daily costs incurred during temporary evacuation and relocation,
- One-time relocation costs resulting from temporary interdiction or permanent condemnation,
- Decontamination costs for a temporarily interdicted area due to habitation restrictions,
- The combined cost of depreciation and loss of use of temporarily interdicted property based on an expected rate of return on investment,
- The value of property that is permanently condemned, and
- Economic losses resulting from crop disposal.

MACCS does not produce an exhaustive set of nuclear accident costs. Because MACCS is an offsite consequence code, MACCS does not evaluate the onsite damages or economic disruptions of the nuclear plant. Other market costs not considered include housing market impacts on property values, potential decontamination in habitable areas, removal of condemned structures, cost of litigation and a compensation system, medical expenses, and impacts on tourism, trade, and the commercial nuclear power industry from stigma effects. However, MACCS does evaluate important metrics related to these categories, including the number of cancer fatalities and other health effects, the number of displaced individuals, and the amount of land contamination. For a comprehensive cost assessment, users can evaluate these other types of nuclear accident costs outside of MACCS. Nosek (2018, pp. 64-92) provides a conceptual overview of the market and nonmarket impacts important to the cost assessment of nuclear accidents.

1.1.6 Radiogenic Health Effects

MACCS is designed to calculate health effects from doses to specific organs (Runkle & Ostmeyer, 1985). Health effects from ionizing radiation are broadly categorized into two main categories, harmful tissue reactions (i.e., deterministic effects) and stochastic effects (i.e., cancer/heritable effects).

Tissue reactions are "health effects that the severity of which varies with the dose and for which a threshold is believed to exist" (Health Physics Society [HPS], n.d.). Tissue reactions include acute effects that may lead to early fatalities (such as hematopoietic, pulmonary, and gastrointestinal syndromes) and early injuries (such as prodromal symptoms, erythema, pneumonitis, and thyroiditis). Early health effects from tissue reactions have a sparing effect when doses are protracted over time, meaning that doses spread over a longer period are less effective at causing the same biological effect. More recently, cognizant bodies have recognized that tissue reactions can also cause late injuries and fatalities from degenerative conditions, including cataracts, cardiovascular disease, and cerebrovascular disease (International Commission on Radiological Protection [ICRP], 2012; National Aeronautics and Space Administration [NASA], 2016). The sparing effect has not been observed in these late effects, and MACCS therefore may not be well suited to address them. However, scientific understanding of how best to model late effects of tissue reactions is still developing.

MACCS calculates the individual risk of early health effects based on acute organ doses to individuals, which account for the sparing effect. MACCS then calculates the expected number of early health effects based on the individual risk. MACCS estimates individual risk of early health effects using sigmoidal-shaped dose-response relationships.

Stochastic effects are health "effects that occur by chance and which may occur without a threshold level of dose, whose probability is proportional to the dose and whose severity is independent of the dose" (HPS, n.d.). These include cancers and heritable effects (also known as genetic effects). In practice, MACCS analyses may not model heritable effects, but MACCS is capable of modeling them assuming heritable risk coefficients are available.

The stochastic health effects models calculate individual risk of a latent cancer based on early and late doses to individuals, and the expected number of latent cancers based on early and late population doses. This is different than the early health effects model, which calculates the expected number of effects from the individual risk rather than population dose.

Stochastic health effects like cancer are uncertain at low doses. MACCS has four dose-response options that allow users to evaluate different dose-response relationships at low doses and create upper and lower estimates. The four dose-response options are the following: linear no threshold (LNT), linear quadratic, annual threshold, and piecewise linear. The LNT option tends to be the most common approach. Users should be aware that the name "linear no threshold" may be somewhat misleading. At low doses, risk calculated by the LNT model in MACCS is adjusted downward by a dose and dose-rate effectiveness factor (DDREF). This factor accounts for the assessment that small doses are less effective than high doses in causing cancer. Therefore, this option may be better described as LNT adjusted by a DDREF, and it is only completely linear when DDREF is set to a value of one.

The annual-threshold and piecewise-linear dose-response options require annual doses, which are the sum of the external doses received during a year and the current-year internal dose contribution from lifetime dose commitments separated into annual periods. Acute, lifetime, and annual doses are weighted by the relative biological effectiveness (RBE), which depend on the type of radiation and can be different for tissue reaction effects and stochastic effects.

1.2 Spatial Grid

MACCS models atmospheric transport, dosimetry, protective actions, socioeconomic impacts and costs, and radiogenic health effects within a two-dimensional polar-coordinate modeling domain known as the spatial grid. The user specifies the MACCS spatial grid with the input parameters NUMRAD (the number of radial intervals), NUMCOR (the number compass sectors), and

SPAEND (the radial distance from the release point to the outside edge of each radial interval). The user can define 16, 32, 48, or 64 compass sectors and up to 35 radial distances in the spatial grid. When a project uses a site data file, the user must ensure that the site file and the spatial grid definitions are consistent. Likewise, the user must also ensure that the number of compass sectors, or wind directions, in the meteorological file is consistent with the number of sectors defined in MACCS.

Grid spacing is typically at smaller intervals close to the site to create a finer spatial resolution at these distances and larger intervals at longer distances. The radial intervals also provide a useful index to report the spatial variation of consequences important to many applications. For NRC applications, results are commonly reported according to spatial distances of 1, 10, 50, and 500 miles.

For doses in the early phase where the spatial distribution of doses may be important for calculating early health effects, MACCS subdivides the (coarse) spatial elements into several fine spatial elements (defined by NUMFIN). This is discussed more in Section 3.2, which covers the off-centerline correction factors.

At the time some older analyses were performed, such as NUREG-1150 (NRC, 1990), sixteen radial sectors was the only option available. More recently, SOARCA analyses divided the problem areas into sixty-four sectors since it provides the highest available degree of grid resolution and allows for a more realistic modeling and resolution of results. This has become the recommended choice for MACCS. This enhancement was implemented in response to the SOARCA peer review (Helton, Khatib-Rahbar, Mubayi, O'Kula, & Li, 2006, p. 7).

To better represent the region around a nuclear site, MACCS calculations can consider spatial variations of populations, economic data, land use data, emergency response characteristics, and other information as inputs on the spatial grid. To consider spatial variations of these input data, MACCS requires a site data file. To not use a site data file, the user gives the parameter POPFLG a value of "UNIFORM." A value of "UNIFORM" requires the user to provide various other parameters (e.g., population density, land fraction) in place of the data from the site file, and MACCS applies these values uniformly throughout the modeling domain instead. To use a site data file, the user gives the parameter POPFLG a value of "FILE."

Users can create a site data file either manually or with the help of the SECtor POPulation and Economic Estimator (SECPOP) SECPOP code. SECPOP is a preprocessing code with economic and population data that can create a properly formatted site data file for any sites within the continental U.S. More information on formatting requirements is available in the WinMACCS User's Guide (SAND-2021-1588).

1.3 Population Cohorts

Instead of specifying a single population that all behaves the same, the user can divide the population in the early phase into different population cohorts. Specifying multiple cohorts is useful for modeling the early phase where segments of the population may react differently or have different protection factors during the emergency response (see Section 4.1). For each cohort, MACCS runs a separate simulation. In the intermediate and long-term phase, MACCS treats all survivors as a single, long-term population, where survivors are all residents in the population that do not die from an early health effect.

MACCS has two ways to specify population data using the parameter POPFLG, and three weighting methods to model how multiple cohorts are distributed across the spatial grid and how output results are combined using the parameter WTNAME.

When POPFLG is a value of "FILE," the user must specify a site data file containing a population for each spatial element. A value of "UNIFORM" means no site data file is used, in which case the user must specify a uniform population density (POPDEN), the radial interval at which the population begins (IBEGIN), and the fraction of the site region covered by land (FRACLD). With the UNIFORM option, the population of a spatial element (starting at IBEGIN) is the area of the spatial element multiplied by POPDEN and FRACLD.

In addition to population, the site data file also specifies the spatial distribution of land fractions, watersheds, and economic regions. When the site data file is not used, MACCS requires the user to provide inputs to specify uniform distributions for other site data as well.

When a site file is used (POPFLG = "FILE"), there are three cohort weighting options: PEOPLE, TIME, and SUMPOP. Without the site data file (POPFLG = "UNIFORM"), there are two weighting factor options: PEOPLE and TIME.

A value of "PEOPLE" allows the user to specify a population fraction F_i for each cohort i using the parameter WTFRAC$_i$. This divides the population into cohorts according to the user-specified fraction F_i. In this option, the population fractions F_i are uniform throughout the site region and must sum to one.

The "SUMPOP" option does not directly specify cohort fractions. Instead, SUMPOP requires multiple population data blocks in the site data file, one for each cohort, where the sum of the population blocks should equal the total population distribution. Instead of a single spatial distribution of the full population (as done in the "PEOPLE" option), the SUMPOP option allows each population cohort to have a different spatial distribution. This gives the user the most flexibility in defining cohorts as the user can directly define the population POP_{in} of each cohort i and spatial element n. The user can either manually create a new site file with a population distribution over the spatial grid for each cohort, or they can use WinMACCS to help create such a new site file. See the WinMACCS User Guide for more information.

Finally, with the "TIME" method, the entire population follows each cohort definition a fraction of the time. For instance, the population may react differently if the accident starts during work hours compared to early morning or the weekend. Since the "TIME" option applies to the full population, MACCS treats each time fraction as basically being a separate consequence simulation. Here, WTFRAC$_i$ represents the fraction of the time or probability that this cohort definition is applicable, and the fractions must sum to one. While the PEOPLE and TIME options produce precisely the same mean results, they produce different quantile results.

The population POP_{in} and the weighting fraction F_{in} of cohort i in spatial element n depend on the cohort modeling option chosen by the user:

$$F_{in} = \begin{cases} F_i & for \quad \text{"PEOPLE" and "TIME" option} \\ \dfrac{POP_{in}}{POP_n} & for \quad \text{"SUMPOP" option} \end{cases} \tag{1-1}$$

And

$$POP_{in} = \begin{cases} F_i \cdot POP_n & for \quad \text{"PEOPLE" and "TIME" option} \\ POP_{in} & for \quad \text{"SUMPOP" option} \end{cases} \tag{1-2}$$

Where

- F_i is the population fraction ("PEOPLE") or the time fraction ("TIME") of cohort *i* for all spatial elements, given by the parameter $WTFRAC_i$,
- POP_{in} is the population of cohort *i* in spatial element *n*, and
- POP_n is the population in spatial element *n* for all cohorts.

In the "PEOPLE" and the "TIME" option, the population POP_n of spatial element *n* is either given by the site data file, or it is based on the spatial element size when using a uniform population density. In the "SUMPOP" option, the population POP_{in} of cohort *i* of spatial element *n* is given by the site data file, and the population POP_n in spatial element *n* is simply the sum across all cohorts, (i.e., $POP_n = \sum_i POP_{in}$).

MACCS uses the weighting fraction F_{in} and the population POP_{in} of cohort *i* in spatial element *n* in Equations (1-3) and (1-4), respectively. These equations combine the cohort results to calculate a set of overall results.

1.4 Computational Framework

The models in MACCS are implemented in three modules: ATMOS, EARLY, and CHRONC.

Each consequence simulation, sometimes called a weather trial, is a single source term paired with a single weather sequence. MACCS has three methods to specify a single weather sequence and run a single weather trial and has two methods to sample many weather sequences and run many weather trials, as discussed in Section 2.3.3. Each MACCS calculation considers a single source term, but a MACCS calculation using a sampling method can have up to 8,760 weather trials, one for each unique weather sequence starting each hour of the year. Additionally, the number of consequence simulations multiplies when using wind rotation. For each consequence simulation, wind rotation creates an additional set of results by rotating the weather conditions by one compass sector, using the same weather sequence each time. Wind rotation is discussed in Section 2.3.2.

Figure 1-1 depicts the progression of a MACCS consequence calculation for one source term, one weather sequence, and one exposed population distribution. The ATMOS module treats the atmospheric dispersion and transport of material and its deposition onto the ground. The EARLY module models emergency response, early doses, and resulting health effects from exposures during the early phase. The CHRONC module models the late doses, intermediate and long-term protective actions, and health effects from exposures during the intermediate and long-term phases. CHRONC also models costs from protective actions during the emergency, intermediate, and the long-term phases.

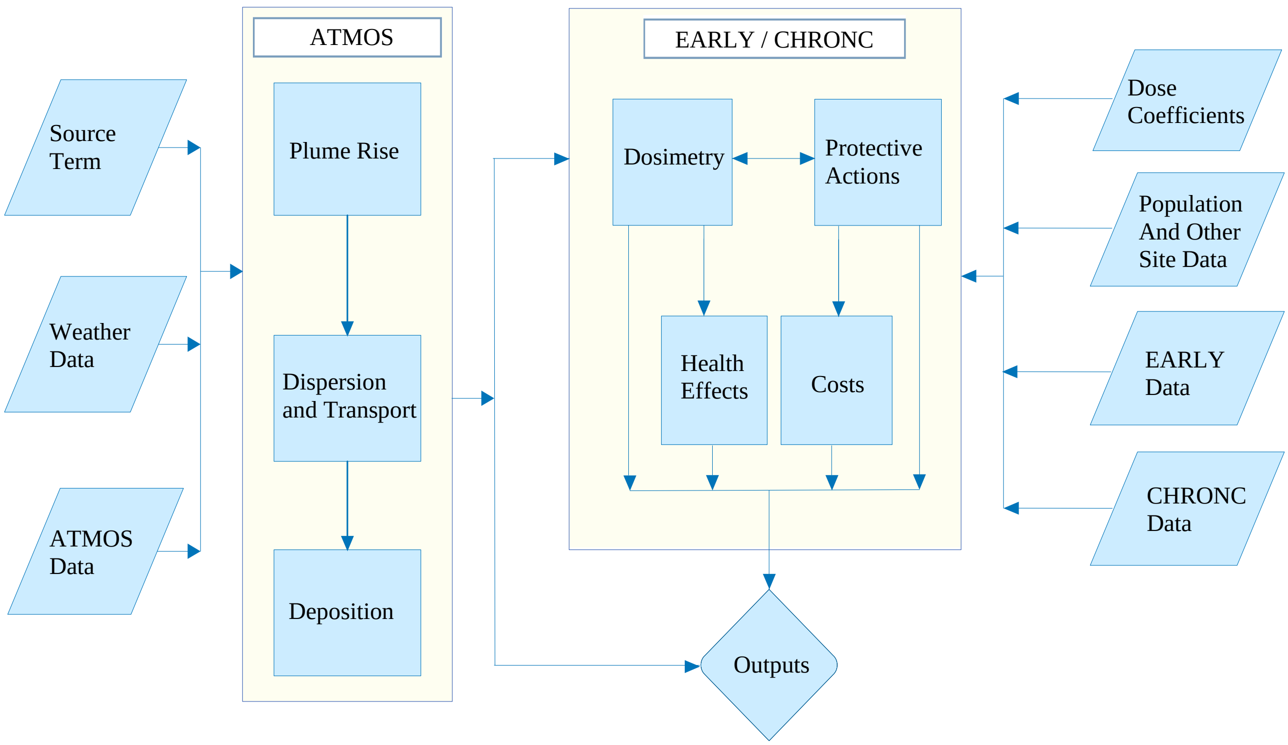

Figure 1-1. Progression of a MACCS Consequence Calculation

1.5 MACCS Outputs

MACCS reports various outputs related to atmospheric transport, dosimetry, socioeconomic impacts and costs, and radiogenic health effects. For most types of output, MACCS provides a complementary cumulative distribution function (CCDF), the data for which MACCS produces when many weather trials are run. Figure 1-2 presents an example CCDF for early fatalities. In the output file, the following statistical results are extracted from a CCDF:

- the probability that any consequences occur (*y*-intercept);
- the expected (mean) consequence magnitude, $E(X) = \sum_i P_i X_i$, where P_i is the probability and X_i is an output result of consequence simulation i;
- the consequence magnitudes that correspond to a set of quantile values (e.g., for any consequence the 90th quantile is the consequence magnitude that has a conditional probability of 0.1 of being equal or exceeded), and
- the largest consequence magnitude calculated for any weather trial (the consequence magnitude that corresponds to the last point on the tail of the CCDF).

For the example shown in Figure 1-2, the probability of having any early fatalities = 0.2; early fatality 90th quantile = 2; and largest result calculated = 30.

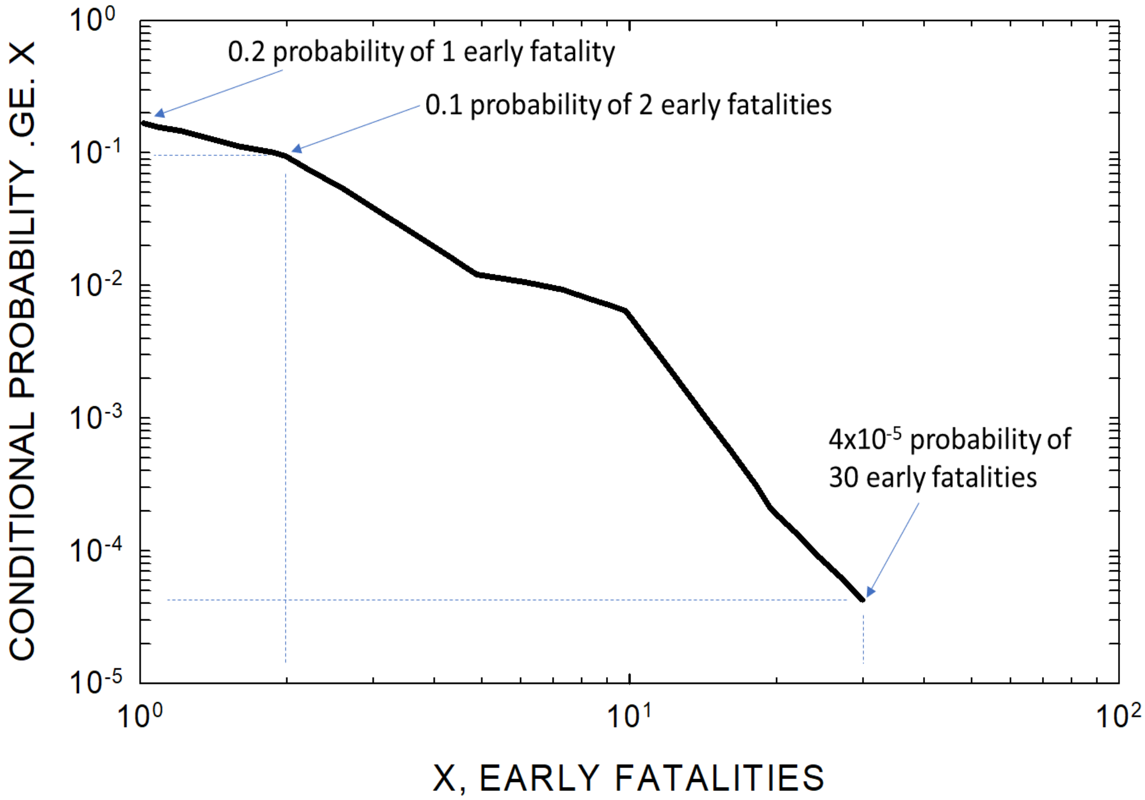

Figure 1-2. An Example of Conditional Early Fatality CCDF

Severe accidents can lead to source terms of quite different magnitudes, and the weather conditions at the time of the release can greatly alter consequence magnitudes (e.g., significant dispersion could cause extensive land contamination, while on the other hand intense rain could concentrate doses and greatly increase early health effects). While consequence metrics tend to increase with greater release magnitudes, the individual output metrics do not generally exhibit a linear response. One reason for this is dose thresholds. For instance, early health effects have a dose threshold, which mean acute doses need to reach a certain level before these effects are observed. Another reason for this is that most protective actions are based on a dose limit. Therefore, for increasing release magnitudes, protective actions tend to limit the increase in dose and associated health effects, but at a tradeoff of causing more land interdiction, displaced individuals, and associated costs.

The end of each section discusses the individual outputs in more detail. Table 1-1 lists the outputs for which MACCS computes a CCDF. To have MACCS report a result in the output, the user must request the output in the applicable MACCS module.

Table 1-1. Results Available from ATMOS, EARLY, and CHRONC

Output Name	ATMOS	EARLY	CHRONC	Notes
Type 0: Atmospheric Results for Specified Downwind Distances	X			See Section 2.9
Type 1: Health Effect Cases		X	X	See Section 6.3
Type 2: Early Fatality Distance		X		See Section 6.3
Type 3: Population Exceeding Early Dose Threshold		X		See Section 3.5
Type 4: Average Individual Risk		X	X	See Section 6.3. Ingestion and decontamination worker doses are not included in the Type 4 results.
Type 5: Population Dose		X	X	See Section 3.5
Type 6: Centerline Dose		X	X	See Section 3.5. Result only available when wind shift is turned off (IPLUME = 1). Ingestion and decontamination worker doses are not included in the Type 6 results.
Type 7: Centerline Risk		X	X	See Section 6.3. Result only available when wind shift is turned off (IPLUME = 1). Ingestion and decontamination worker doses are not included in the Type 7 results.
Type 8: Population-Weighted Individual Risk (i.e., Safety Goal Risk)		X	X	See Section 6.3. Ingestion and decontamination worker doses are not included in the Type 8 results.
Type A: Peak Dose for Specified Distances		X	X	See Section 3.5. Ingestion and decontamination worker doses are not included in the Type A results.
Type B: Peak Dose for Specified Spatial Elements		X	X	See Section 3.5. Ingestion and decontamination worker doses are not included in the Type B results.
Type C: Land Area Exceeding Dose		X		See Section 3.5. Results only available within the individual cohort results. (Results not available within the set of overall results.)
Type C Flag: Dose by Grid Element		X	X	See Section 3.5. Ingestion and decontamination worker doses are not included in the Type C flag results.
Type D: Land Area Exceeding Concentration		X		See Section 3.5. Results only available within the set of overall results.
Type D Flag: Ground Concentration by Grid Element		X		See Section 3.5. Results only available within the set of overall results.
Type E: Population Movement Across Radius		X		See Section 5.4
Type 9: Breakdown of Late Population Dose			X	See Section 3.5

Type 10: Economic Cost Measures			X	See Section 5.4. Results only available when using a food-chain model (FDPATH = “OLD” or “NEW”).
Type 11: Maximum Distance for Protective Actions			X	See Section 5.4. Results only available when using a food-chain model (FDPATH = “OLD” or “NEW”).
Type 12: Impacted Area / Population			X	See Section 5.4. Results only available when using a food-chain model (FDPATH = “OLD” or “NEW”).
Type 13: Maximum Annual Food Ingestion Dose			X	See Section 3.5. Result only available when using the COMIDA2 food-chain model (FDPATH = “NEW”).
Type 14: Evacuated and Relocated Population			X	See Section 5.4

There are many dose and health effect outputs (i.e., Type 1, 4-8, A, and B) that sum the results from the early phase (generated by the EARLY module) with results from the intermediate and long-term phase (generated by the CHRONC module). When the CHRONC module is not run, MACCS still reports these outputs, but they only include early phase portion of the results. When the CHRONC module is run, many of these outputs (i.e., Type 4, 6, 7, 8, A, and B) still do not include food or water ingestion doses or decontamination worker doses. Type 1 and 5 outputs include ingestion and decontamination worker doses when CHRONC is run, making these outputs the most complete of all output types.

Most outputs generated by the EARLY module are cohort specific. This includes EARLY output types except Type D. To calculate an overall result, MACCS combines the EARLY outputs or the EARLY and CHRONC outputs (if applicable) using the formula in Table 1-2. Combining the cohort results to determine the overall early phase result depends on whether the output metric is an individual or collective result. MACCS treats Type 2, 4, 6, 7, 8, A, and B as individual type results, while Type 1, 3, 5, and E are collective results. Note that MACCS does not calculate an overall result for a Type C output.

Table 1-2. Formula for Combining Cohort-Specific Results

Output result type:	EARLY only results	EARLY and CHRONC results	
Individual	$X_n^E = \sum_i X_{in}^E \cdot F_{in}$	$X_n = X_n^E + X_n^L$	**(1-3)**
Collective	$X_n^{E,POP} = \sum_i X_{in}^E \cdot POP_{in}$	$X_n^{POP} = X_n^{E,POP} + X_n^{L,POP}$	**(1-4)**

Where

- X_n and X_n^{POP} are output metrics (e.g., dose, health effects) in spatial element *n* combining the early and long-term phase, for individual and collective results, respectively,

- X_n^E and $X_n^{E,POP}$ are the early phase output metrics (e.g., dose, health effects) in spatial element *n* combining all the cohorts, for individual and collective results, respectively, and calculated by the EARLY module,

- X_{in}^E is the early phase output metric (e.g., dose, health effects) for cohort *i* in spatial element *n* calculated by the EARLY module,

- X_n^L and $X_n^{L,POP}$ are the combined intermediate and long-term phase output metrics (e.g., dose, health effects) in spatial element *n*, for individual and collective results respectively and calculated by the CHRONC module,

- F_{in} is the population fraction of cohort *i* in spatial element *n* given in Equation (1-1), and

- POP_{in} is the population of cohort *i* in spatial element *n* given in Equation (1-2).

Type 6 and Type 7 outputs are centerline results. Therefore, they do not represent a specific spatial element, although they are reported for a specific radial interval. Combining the early phase outputs across different cohorts depends on the cohort model discussed in Section 1.3, as this determines the method for obtaining the population POP_{in} and population fraction F_{in}.

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2 ATMOSPHERIC TRANSPORT

2.1 Introduction

This section discusses all the calculations pertaining to atmospheric transport, including plume rise, dispersion, and deposition. This section also defines the characteristics of an atmospheric release of radioactive material (and the associated radioactive decay and ingrowth), and how it defines meteorological data. Finally, this section discusses how MACCS categorizes and samples uncertain weather to create distribution of results from a set of representative simulations.

The atmospheric transport models estimate the distribution of time-integrated air concentrations and ground concentrations in the site region from an atmospheric release of radioactive material. Additionally, the atmospheric transport models determine plume arrival time, plume departure time, plume dimensions, and other characteristics discussed in Section 2.9. The dosimetry models in Section 3 use the air and ground concentrations to estimate doses to the public through various exposure pathways. The atmospheric transport models calculate results in the radial intervals of the modeling domain, whereas the dosimetry models calculate results in the spatial elements of the modeling domain using plume centerline concentrations and off-centerline correction factors.

The transport models can consider a complex release with a range of aerosol sizes plus gases containing up to 150 radionuclides, and variations in the plume release amount, duration, buoyancy, and other characteristics.

MACCS has three methods for users to specify weather data for the atmospheric transport models. Users can choose constant weather, specify 120 hours of weather data, or specify an external weather file containing one year of meteorological data.

Since the weather at the time of an accident is unpredictable, MACCS supports sampling options to run many accident simulations that consider weather variability when using the weather file. As a surrogate for future weather, MACCS samples time periods that contain changing weather conditions from a year of observed meteorological data. MACCS provides summary statistics of these simulations and optionally reports results as a CCDF.

The transport model can include up to 500 plume segments. While the straight-line Gaussian plume model cannot consider wind trajectory, it can consider wind direction at the point of plume segment release, and it can continue to consider varying meteorological conditions such as stability class, windspeed, precipitation rate, and mixing layer height during transport.

Users can specify the initial dimensions created by building wake effects and one of two plume rise models. MACCS models plume rise when the plume has enough buoyancy to overcome the critical windspeed to escape the ground.

There are several options available for modeling dispersion. MACCS has two plume methods for modeling dispersion as a function of downwind distance. It also includes a time-based dispersion option that a user can invoke beyond a specified downwind distance. MACCS also has the ability to model increased dispersion in the vertical direction due to ground surface roughness, and in the lateral direction from plume meander.

In order to incorporate time-varying weather data during plume segment transport, MACCS uses a mathematical method using a virtual source location. For each new hour of weather, MACCS computes a new virtual source location to calculate changing plume transport characteristics while ensuring continuity in plume dimensions at the transition in weather characteristics.

MACCS models both wet and dry deposition. Dry deposition rate is based on the ground-level air concentrations and a dry deposition velocity. Because deposition velocity depends on aerosol sizes, MACCS categorizes the chemical groups of radioactive material by aerosol size. Wet deposition (e.g., rain) is very efficient for removing radioactive material from the plume. Therefore, unlike dry deposition, it is necessary for MACCS to consider the location of the full plume segment during wet deposition to account for the deposition footprint.

In estimating transport results, the ATMOS module first calculates undecayed air and ground concentrations. Then ATMOS adjusts the concentrations for decay and ingrowth for specific times. Radioactive decay and ingrowth start with the initial inventory specified in the ATMOS input. MACCS considers radioactive decay until the point plume departs the radial interval (i.e., the time when deposition is complete) for calculating early doses, or until the end of the early phase for calculating late doses. After these points in time, MACCS models radioactive decay and ingrowth as part of the dose equations for each exposure pathway, which is discussed in Section 3.

Benchmarking the results from MACCS against more complex models was performed in the analyses documented in NUREG/CR-6853 (Molenkamp, Bixler, Morrow, Ramsdell, & Mitchell, 2004). This study compared MACCS version 2 to ADAPT/LODI, a state-of-the-art, three-dimensional advection dispersion code. The selected site in Oklahoma has relatively flat terrain but is affected by low level nocturnal jets and occasional severe storms. Overall, the arc-average and the great majority of the grid-element-average exposures and depositions calculated by MACCS were within a factor of two of the results computed by LODI (Molenkamp, Bixler, Morrow, Ramsdell, & Mitchell, 2004). Although these results were obtained at a relatively simple terrain site, they do provide a basis for use of a Gaussian model at distances of up to 100 miles.

A recent benchmarking study between the MACCS Gaussian and MACCS/HYSPLIT atmospheric transport and diffusion (ATD) models was performed for five sites and two source terms. The comparison of the Gaussian and HYSPLIT ATD model shows very good agreement for the mean results and good agreement for 5-percentile and 95-percentile results over a broad range of output quantities that were evaluated for distances up to 1000 miles. Most output results were within a factor of two with the HYPSPLIT ATD results typically being higher. The trends as a function of distance for the output quantities also agree well between the two models.

2.2 Atmospheric Source Term

Atmospheric transport modeling for MACCS requires data that define the characteristics of a release, including radionuclide inventory data, plume timing and release fractions, plume release path information, and other plume segment definitions.

The development of a radiological source term is typically based on radiological inventory calculations such as generated by the ORIGEN code (Oak Ridge National Laboratory, 2016) and the atmospheric release characteristics as estimated by an accident progression code capable of tracking airborne releases into the environment, such as MELCOR (Humphries, Cole, Louie, Figueroa, & Young, 2017) or MAAP. The MACCS user is also responsible for other inputs related to the radionuclide release characteristics, which are described in this section.

The user can manually generate atmospheric source-term inputs for MACCS, create them with the MelMACCS preprocessor code, or create them with another code. MelMACCS contains a set of radiological inventories from previous ORIGEN calculations and can read MELCOR plot files. Whether using MelMACCS or generating source term inputs another way, the process is similar. The radionuclides to be included are identified, a radiological inventory is developed, the radionuclides are assigned with a set of chemical groups, and the release of each chemical group as a function of time is discretized into a set of plume segments with information related to physical release height, buoyancy, and magnitude of the released material. The user can obtain most of these inputs from any accident progression code that is capable of tracking airborne releases into the environment.

Accidents with multiple sources, such as a release from two or more reactors or a release from a spent fuel pool with different fuel mixtures may require special consideration in MACCS. Users can model a single source by setting the parameter MSMODL to a value of "FALSE," or can model multiple sources with a value of "TRUE." The multi-source option allows a user to specify plume segments from more than one radionuclide inventory with different accident initiation times and consider the offsite consequences from the combined set of releases.

The MACCS code was originally only designed for a single radionuclide inventory, which is the single source option. Even with one radionuclide inventory, users can specify plume segments with different release fractions and other characteristics. Since MACCS calculates release activity by multiplying the radionuclide inventory by the release fraction, MACCS can still model some variations in release with one inventory. Yet in certain scenarios, such as a multi-unit or a spent fuel pool accident, it is difficult to model distinct releases with only one radionuclide inventory. A possible solution to this is to manually combine the separate inventories and treat them as a single homogenous inventory. However, this is problematic if there is an uneven release across the fuel elements and the fuel inventory is not homogenous. For a single reactor, accident simulations can commonly treat the fuel inventory as being homogenous. For a spent fuel pool, however, it can be important to treat recently discharged fuel elements as a source that is distinct from older fuel, as fuel elements with more decay power are more likely to have both larger release fractions and a greater proportion of short-lived radionuclides.[2] Therefore, certain accident simulations benefit from being able to model more than one inventory.

When using a single source (MSMODL = "FALSE"), MACCS requires the user to specify the source parameters in the ATMOS file. The MelMACCS output matches the ATMOS file format requirements so the user can manually copy the information into the ATMOS file, or the user can

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[2] Note that if the user defines a release fraction for each radionuclide and provides a value that properly weights release from the different zones, the user can model a multi-source term as a single source. However, this information may not be readily available, as the current practice of accident progression codes such as MELCOR is to group isotopes according to their chemical properties. As such, accident progression calculations assuming a homogenous fuel mixture do not distinguish how a disproportional release from the fuel inventory with higher burnup can lead to a relative difference of Cs-134, Cs-136, and Cs-137 release, for instance.

import the MelMACCS output file using the WinMACCS code. When using the multi-source option (MSMODL = "TRUE"), the user specifies an external file containing the parameters for each source. The user can manually create the multi-source input file, or the user can combine MelMACCS source term outputs automatically with the preprocessing code *CombineSource.exe*. This can be done in a WinMACCS project by specifying the location of each MelMACCS source term file, which then uses *CombineSource.exe* to create multi-source, source term input file titled *CombineSource.out*. In addition to the multi-source input file, MACCS requires a time offset (TIMSET) for each source. MACCS uses the time offsets to update the delay to plume release (PDELAY) for each plume segment in the MACCS calculation.

2.2.1 Radionuclide Inventory Characteristics

As parameter inputs, MACCS requires the name ($NUCNAM_i$) and activity ($CORINV_i$) of each radionuclide *i* considered in the analysis as defined at the time of accident initiation, which is commonly chosen to be the time of reactor trip. The time corresponding to this inventory is the reference time in the MACCS framework for notification of the public, delays to plume segment releases, and other emergency response actions. In a typical reactor core, many radionuclides are produced in the core of a nuclear reactor by nuclear fission, decay of fission products, and activation of structural materials. At any given time, the isotopic concentrations in the reactor core depend on the fuel makeup, the reactor design, and the operational history of the fuel assemblies in the reactor core. Ultimately, most radionuclides in a light water reactor are not important for consideration in offsite consequences because of their relatively small inventory, short half-life, low radiobiological hazard, or low volatility leading to a low release fraction, and are commonly excluded from an analysis. MACCS allows up to 150 radionuclides as part of the analysis, and MACCS users can collectively scale the entire radionuclide inventory amount with the input parameter CORSCA.

After atmospheric transport modeling, MACCS adjusts the air and ground concentrations to account for radioactive decay and ingrowth. MACCS accounts for radioactive decay with data provided in the decay chain definition file INDEXR.DAT in the MACCS program directory, which contains the half-lives, decay products, and decay fractions of 825 radionuclides. Between the accident initiation and release into the atmosphere (PDELAY), ongoing radioactive decay forms new decay products not accounted for in the initial core inventory. Because the MELCOR calculation does not consider radioactive decay, the release characteristics (specifically, release fraction and aerosol size distribution) of these new decay products is not self-evident. Therefore, MACCS requires the user to choose how to assign release characteristics to new decay products through the parameter APLFRC. MACCS users can choose to model the new decay products either to have the same release fraction and aerosol size distribution as the parent radionuclide ("PARENT") or as the decay product ("PROGENY"). Neither option is perfect, but the better option depends on the fraction of the decay that occurs before versus after release from the fuel and whether the decay involves a phase change between parent and progeny. Section 2.7.1 discusses the modeling of radioactive decay and ingrowth in more detail.

MACCS requires the radionuclides be assigned into chemical groups of similar physical and chemical properties through the parameter IGROUP. Although it is not standard practice, in principle each radionuclide could be its own chemical group and be specified independently of the other radionuclides because the maximum number of chemical groups, MAXGRP, is the same as the maximum number of radionuclides (i.e., 150). MACCS also requires the user to specify whether the chemical group is subject to dry deposition (DRYDEP) and wet deposition (WETDEP). All radionuclides assigned to the same chemical group are assumed to have identical chemical properties. Properties such as the release fraction and aerosol size distribution are defined according to the chemical group they belong to and are assumed to be the same for all radionuclides within the group. Likewise, accident progression codes such as MELCOR or MAAP model the behavior of the reactor and release inventories also as a set of chemical groups and not as individual radionuclides. The user can assign radionuclides into chemical groups either manually or with the aid of MelMACCS. By assigning chemical groups according to how they are grouped in MELCOR, MACCS can use the atmospheric release characteristics as estimated by the MELCOR accident progression simulation.

2.2.2 Plume Segment Characteristics

Users can discretize the atmospheric release of radionuclides into individual homogeneous plume segments, and MACCS treats each of these segments as a separate plume. MACCS allows users to define up to 500 individual plume segments. The user can discretize the plume segments manually or with the help of the MelMACCS code (McFadden & Bixler, 2015).

Each plume segment travels in the compass direction that matches the wind at the time it is released. To better reflect changing weather conditions, such as during long releases when meteorological conditions are likely to vary, users may discretize the plume into hourly plume segments to allow plume segments to travel in different compass directions. The use of one-hour plume segments takes advantage of the hourly information available in a typical meteorological file. MACCS also allows weather averaging periods to be 15 and 30 minutes.

While plume segments can never change their direction after release, each segment reacts to changes in wind speed, stability class, precipitation rate, and mixing height[3], according to subsequent hours of weather data until the plume segment exits the computational grid. The use of hourly plume segments can also better represent changes in release characteristics, such as release rate.

For each plume segment, MACCS requires the time at which the segment begins to release (PDELAY), the duration of the plume segment (PLUDUR), a fraction of each chemical group that is released with this plume segment (RELFRC), and a reference location within each plume segment (REFTIM). MACCS uses the core inventory ($CORINV_i$), the release fraction, and the time of release to calculate the released activity (Q) of a plume segment, which is an input into the Gaussian plume equations in Section 2.5.1. The reference location is a point along the length of the plume segment.

The weather conditions at the time this point is released determine the plume direction and plume rise. Also, during downwind transport, the reference location represents the location of the plume segment for calculating dispersion, dry deposition, and radioactive decay and ingrowth.

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[3] Only when the flag for mixing height (MAXHGT) is set to the value "DAY_AND_NIGHT." See Section 2.3.4 for more details.

To model the start of plume transport, MACCS requires the elevation of the release (PLHITE) as well as the initial plume dispersion height (SIGYINIT) and width (SIGZINIT) resulting from possible wake effects at the release location. If the release does occur inside a building wake, MACCS requires the building height (BUILDH) to model potential plume liftoff. All these parameters are either characteristics or depend on characteristics of the plant site. For source terms developed by MELCOR, MELCOR may be able to provide the atmospheric release elevation for each release pathway. The user may need to adjust these elevations so that the release height is consistent with the actual grade level of the site. Also, the user may want to verify that all the specific structures associated with the release pathways are fully modeled in MELCOR. MACCS requires the user to develop the initial plume dimensions. If the release occurs inside the wake of a building, the initial plume dimensions will depend on the building height and width. (This is discussed in Section 2.4.1).

To model plume liftoff and plume rise due to buoyancy effects, MACCS also requires either the sensible heat release rate (PLHEAT), or the plume density (PLMDEN) and the rate of mass release (PLMFLA). To model dry deposition, MACCS requires the dry deposition velocity (VDEPOS) of aerosol particles from the plume. All these parameters are either physical properties or depend on physical properties of the release. If using MELCOR and MelMACCS, the accident progression calculations produce time-dependent sensible heat release rate, plume density, and rate of mass release. MELCOR also calculates an aerosol size distribution for each chemical group, although unlike other release characteristics, the aerosol size distributions are not time dependent. Either manually or with MelMACCS, the user can translate the aerosol size distribution into a corresponding distribution of dry deposition velocities (NPSGRP, PSDIST).

The weather sampling algorithms in MACCS require the user to identify the risk-dominant plume segment (MAXRIS). MACCS aligns the release of the risk-dominant plume segment with the meteorological start time of the weather sequence. This ensures that the weather samples align with the most significant release. Plume segments that begin prior to the risk-dominant one are aligned with earlier hours in the weather file. For example, if the first plume segment starts one hour before the plume segment designated by MAXRIS, the first plume segment is paired with weather data for the hour prior to the start of the weather sequence.

2.3 Weather

2.3.1 Weather Data

Atmospheric transport modeling for MACCS requires data for wind speed, wind direction defined in terms of a compass sector the wind is blowing toward, atmospheric stability (defined using the classes in Regulatory Guide 1.23 [NRC, 2007] using values of 1 to 6 to represent stability classes A–F/G), hourly precipitation rate, and mixing heights. MACCS has several options for treatment of meteorological data, which include the ability to directly input weather data (either constant weather conditions for the entire simulation [METCOD = 4] or 120 hours of user-specified weather data [METCOD = 3]), or the ability to extract weather data from an external input file (METCOD = 1, 2, and 5).

When using a weather data file, at least one year of weather data are necessary, preferably from a year that is representative of long-term climatic conditions. A MACCS weather data file commonly has hourly data for wind speed, wind direction, stability class, and precipitation rate, although it can have data for 15-minute and 30-minute, in addition to 1-hour periods, which are often referred to as weather averaging periods because wind direction and speed can fluctuate over very short time intervals. Weather files do not provide hourly mixing height data, as MACCS uses seasonal mixing height data. A MACCS weather file must specify at least four entries for afternoon mixing heights when MAXHGT is set to "DAY_ONLY," or eight entries when using both morning and afternoon mixing heights (i.e., MAXHGT = "DAY_AND_NIGHT"). MACCS requires windspeeds to be at least 0.5 m/s, and reinterprets values below 0.5 m/s to be 0.5 m/s. This avoids division by zero when wind speed approaches 0.

Measurements from a site meteorological program conforming to ANSI/ANS-3.11-2010 or its equivalent typically provide meteorological data for MACCS. The data should follow the requirements of Regulatory Guide 1.23. Observational data at a 10-meter level are typically used for a MACCS meteorological file. Users need to convert observational data to the MACCS format. Depending on the quality of the data, users may also need to account for missing data; a qualified meteorologist should fill in missing data when long data gaps exist. Mixing height data require upper air measurements that are only available at selected locations across the United States. Potential sources of mixing height data include Holzworth (1972) or the U.S. Environmental Protection Agency's (EPA's) Support Center for Regulatory Atmospheric Modeling (SCRAM) upper air databases.[4]

A snippet from a meteorological file is provided in Figure 2-1. Section 7 of the MACCS Users Guide provides an in-depth description of MACCS meteorological files.

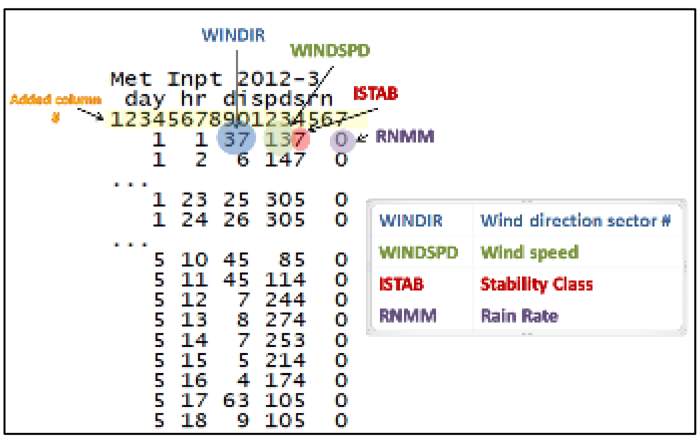

Figure 2-1. Sample Meteorological File Data Format

2.3.2 Weather Modeling

<u>Wind Shift and Rotation Options</u>

MACCS has three main weather modeling options: "no wind shift with rotation" (IPLUME = 1), "wind shift with rotation" (IPLUME = 2), and "wind shift without rotation" (IPLUME = 3). When

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[4] available online at https://www.epa.gov/scram/scram-mixing-height-data

wind shift is allowed (IPLUME = 2 or 3), each plume segment can travel in its own direction according to the weather data during its initial release. Therefore, a shift in the wind direction changes the direction of the next plume segment. If the user instead chooses no wind shift (IPLUME = 1), all plume segments travel in the same direction as the MAXRIS plume segment.

When wind rotation is selected (IPLUME = 1 or IPLUME = 2), MACCS performs a full consequence simulation for each compass direction, rotating all the weather by one compass sector at a time. This produces NUMCOR results for each weather trial. The probability of each result is weighted by the wind rose probability of the initial compass direction to account for weather variability. When no wind rotation is selected (IPLUME = 3), MACCS does not rotate the wind direction. MACCS instead simply uses the wind direction specified by the weather data, and just one result is generated per weather trial. Because MACCS only needs to calculate the atmospheric transport once, wind rotation provides a more computationally efficient way to evaluate weather variability. However, wind rotation assumes that the sequence of weather variations is independent of the initial wind direction, which may not be a good assumption.

With wind rotation, MACCS requires a wind rose probability for each compass direction. The default option (OVRRID = False) allows MACCS to specify the wind rose probabilities. When using a weather bin sampling approach (METCOD = 2), the wind rose probability distribution corresponds to the weather bin data. Otherwise, the default option uses a uniform wind rose probability distribution. The user can specify the wind rose probability distribution (OVRRID = True) using the variable WINROS.

Weather and Source Term Alignment

Weather data are organized into sets of hourly weather data called a weather sequence. To run a calculation, the start time (beginning of the first hour) of a weather sequence needs to be aligned to some point in time during an accident. MACCS requires this point in time to be the release of a user-specified plume segment, sometimes called the risk-dominant plume segment. The user specifies the risk-dominant plume segment (designated by MAXRIS), which then allows MACCS to pair the reference location (designated by REFTIM) of this plume segment to the start time of each weather sequence in a calculation.

The alignment of the risk-dominant plume segment to the first hour of weather is only meaningful for the bin sampling method (METCOD = 2), which is a method for selecting weather data. When using any method other than bin sampling (i.e., METCOD = 1, 3, 4, or 5), the start hour of the weather sequence does not have any special significance. The different methods for selecting weather data are discussed next in Section 2.3.3.

Weather bin sampling is a type of importance sampling, i.e., the algorithm attempts to ensure that adequate sampling is performed for weather conditions according to their potential to cause early fatalities. When using the weather bin sampling method, MACCS uses the weather conditions at the start time of a weather sequence to represent and sort the weather sequences into weather bins. While the initiation of the accident may seem to be the most natural choice for the start time of the weather sequence, the release may not begin until tens of hours later, depending on the nature of the accident. When the release does occur, weather conditions at the beginning of the accident may no longer be representative of the weather conditions during release. Likewise, for a release that begins relatively slowly, aligning weather conditions with the first plume segment may also not be the best choice to represent the weather trial. For this reason, the release of the risk dominant plume segment is the start time of a weather sequence.

Depending on what a user designates for MAXRIS, plume segments may release before the risk dominant segment (e.g., a leak that precedes a large blowdown puff). When this occurs, MACCS requires additional weather data for these early plume segments. When using a weather file (METCOD = 1, 2, or 5), MACCS uses data from the weather file that precedes the start hour of the sequence. If the sequence begins early in the weather file and therefore these data are not available, MACCS loops around and uses data from the end of the weather file to fill in the required data. Similarly, if the user specifies 120 hours of weather data (METCOD = 3), MACCS uses the first hour in the sequence to represent earlier hours.

Plume Reference Location

MACCS models dispersion and dry deposition as though all materials of a plume segment are concentrated at a single location along its length. Furthermore, weather conditions seen by one point along that length must be used for all points along its length. In Calculation of Reactor Accident Consequences (CRAC2) which was a predecessor code to MACCS, this reference location was the plume's leading edge. This was problematic for long-duration releases (i.e., plume segments with release durations of many hours), as changes in wind direction or plume rise after the initial release are essentially ignored and dispersion and dry deposition are modeled as though all plume materials are concentrated at the leading edge of the plume. Furthermore, it was also problematic because the reference location of a plume also affects integrated air and ground concentrations that account for radioactive decay and ingrowth, as these values are calculated in part according to the arrival time of the plume segment reference location. As such, the use of a reference location at some interior point along the length of the segment better represents the average weather conditions along the length of the plume.

MACCS now requires the user select a reference location for each plume segment (REFTIM). The reference location is a fixed point along the length of the plume (usually the segment's leading edge or midpoint). During downwind transport, this point represents the location of the plume segment for calculating dispersion, dry deposition, and radioactive decay and ingrowth, and the weather conditions during the release of this point determine the plume direction and plume rise. Wet deposition does not depend on the reference location, as the wet deposition model assumes the plume material is uniform over the length of the plume segment. Likewise, the dose equations in Section 3 also assume that plume material is uniform over the length of the segment. The user specifies the reference location of a plume segment as a value between zero and one, where zero is the leading edge of a plume segment, one is the trailing edge of a plume segment, and 0.5 is the midpoint.

2.3.3 Weather Sequence Selection

The user can choose one of five methods for specifying the weather data, which is selected with the variable METCOD. Three of these methods involve a single weather sequence and two methods involve sampling from multiple weather sequences. To run a simulation for a single weather sequence, the user can (1) specify constant weather conditions, (2) provide 120 hours of weather data to create their own weather sequence, or (3) specify a starting day and time period in the weather data file.

If the user chooses constant weather conditions (METCOD = 4), the user does not specify the wind direction with the rest of the weather data. Instead, the default wind direction is a uniform probability distribution of all wind directions, assuming wind rotation is being used (IPLUME = 1 or IPLUME = 2). If the user chooses to override the default (OVRRID = True), the user must instead specify a probability distribution of the wind direction (WINROS). If wind rotation is not being used (IPLUME = 3), the wind direction is north.

If the user enters 120 hours of weather data to create their own weather sequence (METCOD = 3), MACCS uses these data for either the first 120 hours or until all plume segments exit the computational grid, whichever comes first. The user specification includes wind direction in this case. All plume segments must begin release before 120 hours.

When using a method that uses a weather data file (METCOD = 1, 2, or 5), MACCS characterizes a weather sequence as a block of sequential weather data from the file and identifies each sequence according to the first hour of data from the block. The weather sequences can overlap, thereby making 8760 unique weather sequences, or more if the weather data averaging periods are less than 1 hour. A simulation uses as much sequential data from the weather data file as required to transport all plume segments through and out of the computational grid. An atmospheric release may have up to 500 plume segments, each of which can start at a different time after the beginning of the release.

If the user chooses a fixed start time (METCOD = 1), the user specifies a specific day (ISTRDY) and hour (ISTRHR) from the weather data file to act as the starting time period of a weather simulation.

There are two methods to specify weather data for multiple weather sequences. Both involve sampling of the 8760 weather sequences derived from the weather data file. The two methods are (1) a weather bin sampling method (METCOD = 2) and (2) a stratified sampling method (METCOD = 5). Despite the names, both sampling methods are actually “stratified.” The weather bin sampling method sorts weather sequences into categories (i.e., bins) according to weather characteristics, such as the occurrence of rain. The sorting and sampling of the weather bin sampling method is discussed in more detail in the next section. Each bin has a probability based on the number of weather sequences assigned to that bin.

The stratified sampling method sorts weather sequences according to the day of the year they begin. For each day, MACCS randomly samples up to 24 weather sequences from each day according to the variable NSMPLS. Because of the way the weather sequences are sorted and sampled, each weather sequence has the same probability of occurrence, that is:

$$P = 1/(samples\ per\ day) \quad \textbf{(2-1)}$$

If NSMPLS is equal to 24 and hourly weather data are used, this method samples all possible weather sequences, a total of 8760.

2.3.3.1 Weather Bin Sampling

Because the weather during an accident is unknown, for many applications, it is important to simulate many types of weather conditions that affect the atmospheric transport and dispersion processes to obtain a full range of potential consequences and to characterize the statistics. Of the two methods in MACCS that users can use to sample weather sequences, the weather bin sampling method is more complex.

<u>Weather Binning Process</u>

The weather bin sampling method sorts all 8760 weather sequences from the weather data file into weather bins and determines the relative frequency of the different weather bins. With this information, MACCS can sample the weather sequences in a manner that ensures that different weather types are represented and properly weighted according to their relative frequency. Compared to a simple random sampling of weather sequences, the weather bin sampling method attempts to better represent each type of weather sequence.

While wind direction (and population centers) are not considered in the binning process, weather sequences in MACCS are otherwise sorted according to their potential to cause early fatalities. Specifically, the bins are sorted based on rainfall within a certain distance of the site and based on atmospheric stability conditions upon release. As such, the two major categories of weather bins are (1) bins with rain events (i.e., rain bins) and (2) bins without rain events (i.e., non-rain bins). A rain event is defined as a weather sequence with rain that commences before the reference location of the MAXRIS plume segment has traveled past the last rain distance. The plume arrival time at a downwind location is the summation of all the time periods until the plume travel distance is reached, as shown in Equation (2-32).

If rain occurs in a weather sequence before the last rain distance, MACCS categorizes the weather sequence into a rain bin according to the distance that rain first starts and the associated rain intensity during that period. The user chooses the rain bins by first specifying the number of breakpoints for the rain intensity (NRINTN) and the number of breakpoints for the rain distance (NRNINT). In turn, this defines "NRINTN + 1" rain intensity intervals and "NRNINT" rain distance intervals, respectively. These values are different because a value greater than the last rain distance is assumed to be a non-rain event. As such, the total number of rain bins is equal to NRNINT * (NRINTN + 1). The user then defines the breakpoint values for the rain distances (RNDSTS) in kilometers and the rain intensities (RNRATE) in millimeters per hour. Since the meteorological data are for a single weather tower (typically at the reactor site), MACCS assumes that rain occurs in the entire region when it rains at the reactor site. MACCS can then sort the rain events into the user-specified bins.

Non-rain bins are sorted according to the stability class and wind speed at the beginning of the weather sequence. While this does not perfectly represent the entire weather sequence, there is still value in categorizing the weather sequences this way as the first hour has the most potential to cause early fatalities (when MAXRIS is properly chosen). Unlike the rain bins, the non-rain bins are fixed within the code and cannot be changed by the user. There are sixteen non-rain bins in MACCS, as defined in Table 2-1. In total, the number of weather bins can range from twenty-four (if eight rain bins are specified) to forty (if twenty-four rain bins are specified). The definition of the weather bins is reported in the output.

A user may wish to design the rain intensity bins and rain distance intervals, used to define the rain bins, according to the distribution of precipitation in the weather file and according to the distance to a populated area and/or the extent of a potential evacuation. Previous experience modeling large and sudden releases reveals that when significant numbers of early fatalities and injuries occur, they are normally associated with stable weather and low wind speeds at the start of the release or with relatively low probability weather events such as rainfall over urban/suburban areas as far as 40 kilometers from the plant site.

Each weather sequence is defined by its first hour of weather data (not counting data proceeding the first hour of the weather data block if needed to characterize releases proceeding the MAXRIS plume segment). In sorting the weather sequences into different weather bins, MACCS looks at each hour of weather data in the weather sequence and uses the following algorithm:

- If it rains in the first hour of the weather sequence, the sequence goes into the closest distance interval rain bin for the corresponding rain intensity.

- If it does not rain in the first hour, MACCS looks for the first occurrence of rain in subsequent hourly weather data and calculates the distance a plume segment would travel before rain occurs based on the hourly windspeeds. This is then compared to rain distances (RNDSTS) of the rain bins. If rain occurs within one of the distance intervals given to the rain bins, the weather sequence goes into the rain bin with a matching distance interval and rain intensity (based on the first occurrence of rain).

- If the subsequent hours of weather data show that no rain occurs within the farthest specified rain distance, the hourly data are classified as a non-rain weather sequence. The weather sequence is then sorted according to its initial stability class and wind speed.

To illustrate the weather sorting and sampling methodology of MACCS, a set of parameters was chosen that define 32 weather bins, which are described in Table 2-1. An example of weather data sorted into these weather bins is shown in Table 2-2. The weather data for this example represent one year of meteorological data for the Grand Gulf plant site. The entire year of data, 8,760 hourly recordings, are sorted into the 32 weather bins.

Using the three steps described above, MACCS looks at the beginning of each weather sequence to determine its weather bin. For example, if the initial hour of weather data is a rain event of 2 mm/hr, this weather sequence goes into bin number 21 shown in Table 2-1. If the initial hour weather data is not a rain event and the wind speed is 15 km/h, MACCS looks at the subsequent weather data. If it rains at 0.4 mm/h in the next hour, this weather sequence goes into bin number 18 in Table 2-1 because when the rain first occurs the plume already has traveled 15 km, which is the second distance interval (10, 16). If neither the first hour nor the next three hours are rain events and they have wind speeds of 6 km/h, 10 km/h, 10 km/h, and 8 km/h, this weather sequence is classified as one of the non-rain bins, since there are no rain weather data until after the farthest distance interval (24, 32). This weather sequence is then sorted by the initial condition, the stability class and wind speed of its first hour of weather data.

Following the binning process, each weather sequence is assigned to one and only one weather bin. Each of the weather bins then includes a set of weather sequences representing the corresponding weather type.

Table 2-1 Descriptions of Example Weather Bins

Bin Number	Bin Notation*		Description of Weather Sequences in the Bin
	Class	Wind Speed	
1	B	3	Initial stability classes A and B, with initial windspeed ≤ 3 m/s.
2	B	4	Initial stability classes A and B, with initial windspeed > 3 m/s.
3	D	1	Initial stability classes C and D, with initial windspeed ≤ 1m/s.
4	D	2	Initial stability classes C and D, with initial windspeed > 1 and ≤ 2 m/s.
5	D	3	Initial stability classes C and D, with initial windspeed > 2 and ≤ 3 m/s.
6	D	4	Initial stability classes C and D, with initial windspeed > 3 and ≤ 5 m/s.
7	D	5	Initial stability classes C and D, with initial windspeed > 5 with and ≤ 7 m/s.
8	D	6	Initial stability classes C and D, with initial windspeed > 7 m/s.
9	E	1	Initial stability class E, with initial windspeed ≤ 1m/s.
10	E	2	Initial stability class E, with initial windspeed > 1 and ≤ 2 m/s.
11	E	3	Initial stability class E, with initial windspeed > 2 and ≤ 3 m/s.
12	E	4	Initial stability class E, with initial windspeed > 3 m/s.
13	F	1	Initial stability class F, with initial windspeed ≤ 1 m/s.
14	F	2	Initial stability class F, with initial windspeed > 1 and ≤ 2 m/s.
15	F	3	Initial stability class F, with initial windspeed > 2 and ≤ 3 m/s.
16	F	4	Initial stability class F, with initial windspeed > 3 m/s.
17	R1	10	First occurrence of rainfall of intensity 1 in the interval (0, 10) kilometers from site.
18	R1	16	First occurrence of rainfall of intensity 1 in the interval (10, 16) kilometers from site.
19	R1	24	First occurrence of rainfall of intensity 1 in the interval (16, 24) kilometers from site.
20	R1	32	First occurrence of rainfall of intensity 1 in the interval (24, 32) kilometers from site.
21	R2	10	First occurrence of rainfall of intensity 2 in the interval (0, 10) kilometers from site.
22	R2	16	First occurrence of rainfall of intensity 2 in the interval (10, 16) kilometers from site.
23	R2	24	First occurrence of rainfall of intensity 2 in the interval (16, 24) kilometers from site.
24	R2	32	First occurrence of rainfall of intensity 2 in the interval (24, 32) kilometers from site.
25	R3	10	First occurrence of rainfall of intensity 3 in the interval (0, 10) kilometers from site.
26	R3	16	First occurrence of rainfall of intensity 3 in the interval (10, 16) kilometers from site.
27	R3	24	First occurrence of rainfall of intensity 3 in the interval (16, 24) kilometers from site.
28	R3	32	First occurrence of rainfall of intensity 3 in the interval (24, 32) kilometers from site.
29	R4	10	First occurrence of rainfall of intensity 4 in the interval (0, 10) kilometers from site.
30	R4	16	First occurrence of rainfall of intensity 4 in the interval (10, 16) kilometers from site.
31	R4	24	First occurrence of rainfall of intensity 4 in the interval (16, 24) kilometers from site.
32	R4	32	First occurrence of rainfall of intensity 4 in the interval (24, 32) kilometers from site.

*Bin Notation

Non-rain bins (numbered 1-16) have a bin notation based on stability class and windspeed. The notation for stability classes are: B (stability class A/B), D (stability class C/D), E (stability class E), and F (stability class F). The notation for windspeed are: 1 (0-1 m/s), 2 (1-2 m/s), 3 (2-3 m/s), 4 (3-5 m/s), 5 (5-7 m/s), 6 (> 7 m/s).

Rain bins have a bin notation based on rain intensity and rain distance interval. In general, there can be between 8 and 40 rain bins, depending on the number of user-specified rain intensity breakpoints and rain distance endpoints.

In this example, the rain bins are numbered 17-32. The notation for rain intensity level (R1 through R4) correspond to a user-specified value for the rain intensity breakpoints of 0.5, 2.5, and 15.0 mm/hr. The notation for the rain distance interval is also a user-specified value and denotes the interval endpoints of 10, 16, 24, and 32 kilometers.

Table 2-2 Example of Meteorological Data Summarized Using the Weather Bin Algorithms for MACCS (One Year of Grand Gulf Site Weather)

Weather Bin Definitions (See Table 2-1)				
Bin Number	**Weather Bin**		**Number of Sequences**	**Percentage of Hourly Data**
1	B	3	1,250	14.27
2	B	4	384	4.38
3	D	1	200	2.28
4	D	2	560	6.39
5	D	3	501	5.72
6	D	4	564	6.44
7	D	5	84	0.96
8	D	6	1	0.01
9	E	1	498	5.68
10	E	2	604	6.90
11	E	3	306	3.49
12	E	4	192	2.19
13	F	1	1,379	15.74
14	F	2	509	5.81
15	F	3	69	0.79
16	F	4	2	0.02
17	R1	10	457	5.22
18	R1	16	172	1.96
19	R1	24	203	2.32
20	R1	32	163	1.86
21	R2	10	197	2.25
22	R2	16	39	0.45
23	R2	24	41	0.47
24	R2	32	35	0.40
25	R3	10	191	2.18
26	R3	16	29	0.33
27	R3	24	46	0.53
28	R3	32	32	0.37
29	R4	10	36	0.41
30	R4	16	6	0.07
31	R4	24	5	0.06
32	R4	32	5	0.06
Total =			8,760	100.00

Bin Sampling Process

There are between 24 and 40 weather bins of various sizes. The probability of occurrence of each weather bin is the fraction of weather sequences in the bin to the total number of weather sequences in the weather data set of 8,760 sequences, assuming hourly data.

MACCS does not use simple random sampling within the weather bins. Instead, each weather bin i is first subdivided into K_i number of subsets, and then MACCS randomly selects one weather sequence from each subset. As such, K_i is both the number of subsets and the number of weather sequences sampled from each weather bin *i*. Each weather bin subset S_j where *j* is the subset index between $[1, \ldots, K_i]$ is roughly equal in size and are ordered in time. The weather binning process ensures that the model represents a range of weather conditions and subdividing the weather bins into subsets ensures that the model represents a range of dates over the full year.

The user has two options for selecting the number of weather sequences from the weather bins. In the uniform bin sampling option, MACCS samples the same number of weather sequences from each bin. In this method, the user specifies the number of samples to draw from each bin with the parameter NSMPLS. In the non-uniform bin sampling option, the user can select a different number of samples from each weather bin. This is done by setting the variable NSMPLS to zero and individually specifying the number of samples to be drawn from each bin with the variable INWGHT_i for weather bin *i*. With either option, random samples are drawn from approximately evenly spaced subsets within a weather bin.

It may not be possible to divide weather bins into exactly equal-sized subsets. Assume that a weather bin *i* contains N_i weather sequences and that K_i samples are selected from each weather bin. When $K_i \geq N_i$, all the weather sequences N_i in weather bin *i* are selected. Typically, though, K_i is less than N_i, $[0 < K_i < N_i]$. In this case, the N_i weather sequences of weather bin *i* are divided into K_i evenly spaced subsets, $S_1 \ldots, S_{K_i}$. The number of weather sequences contained in subset S_j is then the following:

$$\text{INT}\left[j \cdot \left(\frac{N_i}{K_i}\right)\right] - \text{INT}\left[(j - 1) \cdot \left(\frac{N_i}{K_i}\right)\right] \tag{2-2}$$

where

- $\text{INT}[X]$ represents the integer function that returns the integer part of a real number X (e.g., $\text{INT}[2.5] = 2$).
- N_i is the number of weather sequences in weather bin *i*, determined by the weather binning process described in the section above.
- K_i is the number of samples to be selected from weather bin *i*, specified either by NSMPLS (or by INWGHT_i when NSMPLS is set to zero).
- j is an index for the weather sample randomly selected from the subset S_j of weather sequences within a weather bin.

Since the N_i weather sequences of weather bin *i* have a natural order determined by the initial time of each of the weather sequences, the evenly spaced subsets $S_1, \ldots, S_{K_i}$ of weather bin *i*, are ordered in time. Thus, S_1 consists of the first INT $\left[\frac{N_i}{K_i}\right]$ elements of weather bin *i*, S_2 consists of the next $\left(\text{INT}\left[2\left(\frac{N_i}{K_i}\right)\right] - \text{INT}\left[\frac{N_i}{K_i}\right]\right)$ elements of weather bin *i*, and so on. One weather sequence is then randomly selected from each subset.

Since the total number of weather sequences selected from weather bin *i* is K_i, the total number of sequences selected from a case using 32 weather bins is the following:

$$\sum_{i=1}^{32} K_i \tag{2-3}$$

The assigned probability for a meteorological sequence sampled from weather bin *i* is the following:

$$\frac{1}{K_i} \cdot \frac{N_i}{\sum_{i=1}^{32} N_i} = \frac{N_i/K_i}{\sum_{i=1}^{32} N_i} \tag{2-4}$$

Consider a simple example. Let weather bin *i* contain ten weather sequences from which four are to be sampled. Then $N_i = 10$, $K_i = 4$, and using Equation (2-2) S_1 contains two sequences, S_2 contains three sequences, S_3 contains two sequences, and S_4 contains three sequences. One sequence is drawn from each subset S_j using simple random sampling, as illustrated in Figure 2-2 below. In this figure, an "x" denotes the initial hour that defines each weather sequence in the bin and a circle around an x indicates the selection of that start hour by the sampling procedure.

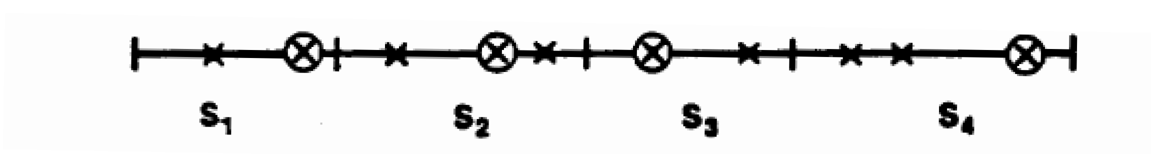

Figure 2-2 Example of Sequences Selected

The assigned probability for a sequence chosen from this weather bin is (10/4)/8760, since MACCS requires the weather data to contain 8760 sequences when hourly data are used.

The sampling technique described here ensures selection of sequences that represent the range of weather conditions. Adequate sampling of each weather bin is the key to a realistic representation of the potential range of weather events.

The MACCS variable IRSEED ensures that the random number generator produces a consistent set of weather trials among different MACCS runs with the same weather data file, in which case differences between different MACCS executions can only be from changes in MACCS parameters but not from sampled weather. A set of runs with identical bin definitions (as defined by NRINTN, RNRATE, NRNINT, and RNDSTS), IRSEED, and either NSMPLS (for uniform bin sampling) or INWGHT (for non-uniform bin sampling), use the same random set of weather sequences.

2.3.4 Mixing Height Model

The mixing height (the top of the well-mixed surface layer of air, frequently the location of the lowest lying temperature inversion in the temperature structure of the surface layer) inhibits both buoyant plume rise and vertical dispersion of plume segments. The mixing height can vary season by season. In addition, throughout the day, the depth of the well-mixed layer normally increases from several hundred meters at sunrise to several thousand meters by mid-afternoon (Holzworth, 1972). MACCS assumes that mixing height does not vary with stability class.

MACCS can model the mixing height in one of two ways. When the flag for the mixing height model (MAXHGT) is set to a value of "DAY_ONLY," MACCS only uses the afternoon mixing heights. That is, the mixing height only depends on the season for which the calculation is performed, not on time of day.

When the flag for the mixing height model is set to the value "DAY_AND_NIGHT," MACCS considers both morning and afternoon mixing height values, and the mixing height of a plume segment changes depending on time of day. When the starting release time of a plume segment is between sunset and sunrise, the morning value for the appropriate season is used until the first hour after sunrise. Between the hour of sunrise and the hour of sunset, the mixing height (of both new and existing plume segments) increases according to a linear interpolation between the morning value and the afternoon value for that season. Once the first sunset in the simulation is reached, existing plume segments use the afternoon mixing height for the remainder of time that the plume segment is in the computational grid. The mixing height is never allowed to decrease in the MACCS treatment because that would violate the second law of thermodynamics. If a new plume segment has a start time after sunset, the mixing height model uses the morning value for this plume segment, and the process repeats.

Calculations based on time of day, such as the mixing height model, require the user to supply the latitude and longitude of the accident site. Sunrise and sunset are calculated according to the site latitude. No adjustments are made to account for the east/west location of a site within a time zone and no adjustments are made for daylight savings time as the weather data file only considers standard time. Thus, MACCS does not directly use the longitude value in any models.

2.3.5 Boundary Weather

MACCS has the capability to apply a user-specified set of weather conditions at a pre-defined radial interval, a capability known as boundary weather. The user must specify values for the boundary weather conditions, these being the mixing layer height (BNDMXH), stability class (IBDSTB), rain rate (BNDRAN), and windspeed (BNDWND).

The user can define where boundary weather begins, which is outside the radial interval specified by LIMSPA. If the user does not want MACCS to use boundary weather, at least not at a pre-defined distance, the user should set LIMSPA equal to the last radial interval in the computational grid.

Another option is to use boundary weather to artificially deplete the plume, thereby ensuring that all the aerosols in a plume segment are deposited on the ground before the segment completely traverses the computational grid. To do this, the user should set LIMSPA equal to (at least) one less than the last radial interval and specify a boundary weather either with a very low windspeed (allowing dry deposition to deplete the plume segment of aerosols completely) or with a high rain rate (which causes aerosols to be removed by wet deposition). If boundary weather is used at distances closer than 500 miles, artificially depleting the plume is not recommended.

In addition to using boundary weather at a specific radial distance, MACCS can also use the user-specified boundary weather values for other purposes, depending on the choice of weather modeling. If the user selects constant weather (METCOD = 4), MACCS uses the boundary weather values as the source of weather data over the entire grid. Note that this is the only situation that MACCS uses the boundary layer mixing height value (BNDMXH), as MACCS does not update the mixing height when defined elsewhere, such as in the weather data file.

When the user provides 120 hours of weather data (METCOD = 3), MACCS uses the boundary weather values if the simulation requires more than 120 hours. Depending on the length of release, the windspeeds, and the last radial distance of the computational grid, a 120-hour period may not be long enough to carry all the plume segments fully out to the last radial interval. If necessary, MACCS supplements the missing information with boundary weather values. If using a weather data file (METCOD = 1, 2, or 5), MACCS considers 1,200 hours of weather data from the weather data file instead of 120 hours. Because the maximum value of PDELAY is 720 hours (30 days) and the minimum windspeed is 0.5 m/s, a calculation is highly unlikely to exceed 1,200 hours. So, MACCS only uses boundary weather conditions outside the radial interval denoted by LIMSPA. If the user anticipates using boundary weather values for any of these other scenarios, the user should verify that the values are reasonably representative of the site or region.

2.4 Atmospheric Release

2.4.1 Wake Effects

MACCS does not directly model building wake effects. Instead, if there is building wake, it is up to the user to specify the initial plume width (SIGYINIT) and height (SIGZINIT) of the gaussian plume segments that are emitted from building wakes. The initial plume dimensions must be larger than 0.1 meters. To incorporate the initial plume dimensions into the Gaussian plume equations, MACCS treats this initial dispersion by means of a virtual release point upwind of the actual release location. See Section 2.5.4 for more information.

One method to estimate the building wake dimensions from a ground-level release in the middle of a downwind face of a building is to assume that 10% of the plume centerline concentrations exist at the building edges and roofline, which corresponds to 2.15 standard deviations from the plume centerline. Assuming that this method is reasonable for most releases, users commonly estimate the initial plume dimensions with the following relationship:

$$\sigma_{y,init} = \frac{W_b}{4.3} \text{ and } \sigma_{z,init} = \frac{H_b}{2.15} \tag{2-5}$$

Where

- $\sigma_{y,init}$ is the initial plume width (SIGYINIT),
- $\sigma_{z,init}$ is the initial plume height (SIGZINIT),
- W_b is the width (m) of the building from which release occurs, and
- H_b is the height (m) of the building from which release occurs.

2.4.2 Plume Rise

Plume segments that are hot (contain appreciable sensible heat) or that contain gases that are less dense than the surrounding atmosphere are buoyant and may rise to heights much greater than their initial release height. However, plume liftoff depends on both the buoyancy flux and the height of the building, and it may not occur if the prevailing windspeed at the time of release exceeds a critical windspeed.

If a plume is not captured within a building wake (i.e., if liftoff occurs), the amount of plume rise depends on the initial atmospheric conditions of the plume segment during release. MACCS models plume rise until it is terminated by any of the following conditions:

- When the plume reaches its final amount of rise Δh_f, which depends on atmospheric conditions and is defined below.

- When the height of the plume centerline reaches the mixing height (height of the capping inversion layer).

- When one hour has elapsed since release of the plume segment began.

To calculate the amount of plume rise, MACCS has two alternative plume rise models known as the "improved" plume rise model and the "original" plume rise model, both of which are based on the work of Briggs.[5] For both models, the amount of plume rise also depends on the stability class and other factors described in more detail below in Section 2.4.2.2.

The improved plume rise model is recommended over the original MACCS plume rise model based on benchmarking analyses with a mechanistic model (the ALOFT-FT code created by NIST). The improved plume rise model is much closer to matching the mechanistic model than the original MACCS plume rise model. The user can select the improved Briggs model by setting the MACCS variable BRGSMD to a value of "IMPROVED."

Both the original and improved plume rise models reflect buoyancy effects but not momentum effects. If momentum effects are important, such as for an explosive release, users may instead be able to specify initial plume dimensions (SIGZINIT, SIGYINIT) for the scenario.

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[5] An unusual aspect of the two plume rise models is that the recommended "improved" plume rise model was published earlier than the "original" model that is no longer recommended. Usually, more recent work represents an improvement over previous work.

2.4.2.1 Plume Liftoff

When wind speeds are high, a buoyant plume segment that is released into a building wake is unable to escape from the wake. In MACCS, escape of a buoyant plume segment from a building wake is governed by a liftoff criterion that was originally proposed by Briggs (1973) and validated by experiments performed at the Warren Spring Laboratory in Great Britain (Hall & Waters, 1986). The criterion states that plume rise occurs only when the wind speed upon release of the segment is less than a critical wind speed u_c that is calculated using the following formula:

$$u_c = \left(\frac{9.09F}{H_b}\right)^{\frac{1}{3}} \quad \textbf{(2-6)}$$

Where

- H_b is the height (m) of the building from which the plume escapes (BUILDH), and
- F is the buoyancy flux (m^4/s^3) of the plume segment, as calculated below in Section 2.4.2.3.

While the value 9.09 is fixed in the code, MACCS has a linear scaling factor (SCLCRW) that acts as a multiplier on the critical wind speed. The user can change SCLCRW to make liftoff more or less likely.

According to the plume liftoff criterion, there is little possibility of plume liftoff due to sensible heat when the release rate is less than 100 kW for a typical, 50-m high, reactor or containment building. When the rate of release of sensible heat is 1 MW, the plume only lifts off when wind speed is less than approximately 1.2 m/s. Larger release rates of sensible heat, like 10 MW, produce lift off under most weather conditions and sites.

2.4.2.2 Plume Rise Equations

MACCS models plume rise when the plume liftoff criterion is met. If plume rise occurs, plume rise also depends on atmospheric stability. Unlike dispersion rate models, plume rise models assume atmospheric stability and windspeed do not vary once release of the plume segment reference location begins.

There are two plume rise models. The user can choose the improved model by giving the MACCS parameter BRGSMD a value of “IMPROVED” or can choose the original model by BRGSMD a value of “ORIGINAL.” Both models treat plume rise using formulae for a buoyant plume.

Two major characteristics of plume rise are the plume trajectory during plume rise, $\Delta h(x)$, and the final amount of plume rise, Δh_f, both of which are defined relative to the initial release height (PLHITE). Both models define the final amount of plume rise, Δh_f, and in most cases, the models also define the plume rise trajectory, $\Delta h(x)$. The exception is the original Briggs model, which does not model a plume rise trajectory for stable atmospheric conditions (stability class E or F). Instead, the model assumes that the plume reaches its final amount of rise when it begins to travel downwind. Under stable conditions, the actual plume rise trajectory likely occurs quickly relative to its downwind transport and its trajectory is unlikely to significantly impact downwind doses.

When MACCS models plume trajectory $\Delta h(x)$, it uses the Briggs "two-thirds law" for bent-over plumes (Hanna, Briggs, & Hosker, 1982):

$$\Delta h(x) = \frac{1.6 F^{\frac{1}{3}} x^{\frac{2}{3}}}{\bar{u}} \qquad \begin{array}{l}\text{Briggs improved model: Any stability class} \\ \text{Briggs original model: Stability class A-D}\end{array} \tag{2-7}$$

where

- $\Delta h(x)$ is the plume rise (m), as measured from the initial release height (PLHITE),
- x is downwind distance (m),
- F is the buoyancy flux (m^4/s^3) of the plume segment, as calculated below in Section 2.4.2.3,
- $\bar{u}$ is the wind speed (m/s) averaged between the initial release height and the final centerline height (h_f), which is discussed below in Section 2.4.2.4

MACCS assumes plumes do not penetrate the boundary mixing layer. If the final plume centerline height is calculated to be higher than the mixing layer, or if plume rise continues after one hour, MACCS truncates plume rise before it reaches the final rise height determined in the plume rise models.

For unstable or neutral atmospheric conditions (stability classes A-D), the MACCS improved plume rise model determines the amount of plume rise using the following formulae based on the work of Briggs (1970):

$$\Delta h_f = \begin{cases} \dfrac{38.7 \cdot F^{0.6}}{\bar{u}} & if \quad F \geq 55\, m^4/s^3 \\ \dfrac{21.4 \cdot F^{0.75}}{\bar{u}} & if \quad F < 55\, m^4/s^3 \end{cases} \tag{2-8}$$

In the original MACCS plume rise model, the following equation determines the amount of plume rise for stability classes A through D (Briggs, 1975):

$$\Delta h_f = \frac{300F}{\bar{u}^3} \tag{2-9}$$

While the values 38.7, 21.4, and 300 are fixed in the code, MACCS has a linear scaling factor (SCLADP) for the plume rise under unstable and neutrally stable conditions (stability classes A-D) that acts as a multiplier on the final plume rise, Δh_f. The user can change SCLADP to decrease or increase the final amount of plume rise, assuming that plume rise is not limited by either the mixing layer height or by the one-hour limit.

Use of the SCLADP parameter for plume rise under neutral or unstable conditions is appropriate with the MACCS original plume rise model, in which final plume rise under neutral or stable conditions is proportional to $\frac{F}{\bar{u}^3}$ (cf., Equation 80 of Briggs [1975]), where the leading coefficient can vary from 200 to 400, and for which the original MACCS plume rise model assumes a value of 300 based on the discussion in Section 5.1 of Briggs (1975). When using the original MACCS plume rise model, a scale factor from 0.36 to 1.8 results in a range of about 100 to 500 for the leading coefficient.

When atmospheric conditions are stable (stability classes E or F), the amount of plume rise, Δh_f, in the improved Briggs model depends on the downwind distance x_f where the plume is expected to reach its final rise height, which in turn depends on the buoyancy flux F. The plume rise Δh_f during stable conditions in the improved Briggs model is the following:

$$\Delta h_f = \begin{cases} 2.4\left(\frac{F}{\bar{u}S}\right)^{\frac{1}{3}} & if \quad x_f > 1.84\frac{\bar{u}}{\sqrt{S}} \\ \text{Equation } (\mathbf{2\text{-}8}) & if \quad x_f \le 1.84\frac{\bar{u}}{\sqrt{S}} \end{cases} \tag{2-10}$$

Where

$$x_f = \begin{cases} 119 \cdot F^{0.4} & if \quad F \ge 55\, m^4/s^3 \\ 49 \cdot F^{0.625} & if \quad F < 55\, m^4/s^3 \end{cases} \tag{2-11}$$

And where

- Δh_f is the final amount of plume rise (*m*), starting from the initial release height (PLHITE),
- F is the buoyancy flux (m^4/s^3) of the plume segment, as calculated below in Section 2.4.2.3,
- $\overline{u}$ is the wind speed (*m/s*) averaged between the initial release height and centerline height (*h*), which is also calculated below in Section 2.4.2.4,
- S is the stability parameter (s^{-2}), which is fixed in the MACCS code (5.04×10^{-4} s^{-2} for stability class E and 1.27×10^{-3} s^{-2} for stability class F) and is also calculated later in Section 2.4.2.5, and
- x_f is the downwind distance (*m*) where the plume reaches its final rise height.

When the downwind distance where the plume levels off is small (i.e., $x_f \le 1.84\frac{\overline{u}}{\sqrt{S}}$), MACCS assumes the plume behaves identically to the improved Briggs model for unstable conditions in Equation (2-8). When $x_f > 1.84\frac{\overline{u}}{\sqrt{S}}$, which is the more likely case for stable atmospheric conditions, MACCS models plume rise according to formula shown in Equation (2-10) based on the work of Briggs (Hanna, Briggs, & Hosker, 1982)[6].

In the MACCS original Briggs model, during stable atmospheric conditions (stability class E or F), MACCS models plume rise using a single, slightly modified version of the previous equation:

$$\Delta h_f = 2.6\left(\frac{F}{\bar{u}S}\right)^{\frac{1}{3}} \tag{2-12}$$

While the values 2.4 and 2.6 are fixed in the code, MACCS has a linear scaling factor (SCLEFP) for the plume rise under stable (stability classes E or F) conditions that acts as a multiplier on the amount of plume rise, Δh_f. Briggs (1975) reports that the leading coefficient for plume rise under stable conditions can range from 1.8 (less plume rise) to 3.4 (more plume rise). With a base value of 2.4 for the improved model, this translates to a range for SCLEFP of 0.75 to 1.4.

2.4.2.3 Buoyancy Flux

Buoyancy flux is an important value that MACCS uses to calculate the plume liftoff, plume trajectory, and the final amount of plume rise. MACCS has two methods to calculate the buoyancy flux F, which are named the "Power Model," and the "Density and Flow Model." The user can select the "Power Model" by setting the MACCS variable PLMMOD to a value of "HEAT". In the Power Model, MACCS calculates buoyancy flux F from the sensible heat release rate $\dot{Q}$ (PLHEAT). The buoyancy flux F is related to the sensible heat release rate $\dot{Q}$ according to the following formula (Briggs G. A., 1965):

$$F = \frac{g}{\pi C_p \rho_a T_a}\dot{Q} \tag{2-13}$$

Where

- F is the buoyancy flux (m^4/s^3) of the plume segment
- g is acceleration due to gravity (9.8 m/s^2)
- C_p is specific heat of air at constant pressure at ambient temperature and pressure (1.005 *kJ/kg-K*)
- ρ_a is density of air at ambient temperature and pressure (1.178 kg/m^3)
- T_a is ambient temperature (300 *K*)
- $\dot{Q}$ is sensible heat release rate (*watts*) of a plume segment, as given by the parameter PLHEAT

[6] Note that although MACCS uses a coefficient of 2.4, there are a number of different values for the value of the leading coefficient. Briggs (1970) Equation 4 gives a value of 2.9. Table 4 of Briggs (1975) shows a range of values from 1.8 to 3.4 and recommends a value of 2.6, which is the value recommended in Equation 2-19 of Hanna, Briggs, & Hosker (1982). This is the value used in the MACCS2 1.12 original plume rise model. Because the amount of plume rise is linear with respect to the leading coefficient, adopting the more common coefficient would result in a slight increase in plume rise.

MACCS assumes standard atmospheric conditions (i.e., 300 K and 1 atm) for the buoyancy flux. As such, the buoyancy flux simplifies to the following:

$$F = 8.79 \times 10^{-6} \cdot \dot{Q} \qquad \textbf{(2-14)}$$

Where the coefficient of 8.79×10^{-6} is fixed in the code. Alternatively, the "Density and Flow Model" can calculate the buoyancy flux *F* from the density (PLMDEN) and mass flow rate (PLMFLO) of the release. The user can select this model by setting the MACCS variable PLMMOD to a value of "DENSITY." In this model, MACCS calculates the buoyancy flux *F* with the following formula:

$$F = \frac{g}{\pi}\left[1 - \frac{\rho}{\rho_a}\right]\frac{\dot{m}}{\rho} \qquad \textbf{(2-15)}$$

Where

- ρ is the density of the plume segment (kg/m^3), as given by the parameter PLMDEN,
- $\dot{m}$ is the mass flow rate of the plume segment (kg/s), as given by the parameter PLMFLO, and
- ρ_a and g are the same as before.

Unlike the Power Model, this method is also able to account for the release of gases that are less dense than air, such as hydrogen and steam.

2.4.2.4 Average Windspeed

Average windspeed is an important value that MACCS uses to calculate both near-field plume trajectory and the final amount of plume rise. Since windspeeds generally increase with altitude, if the plume rise models were to use surface windspeeds they would overestimate plume rise and produce nonconservative ground-level concentrations near the source. Since this could produce a significant underestimation of radiation exposures, for purposes of calculating plume rise, MACCS uses a windspeed averaged between the windspeed at the point of release and the windspeed at the final plume centerline height. The windspeed as a function of height is represented as follows (Hanna, Briggs, & Hosker, 1982):

$$u = u_0 \left(\frac{h}{h'}\right)^p \qquad \textbf{(2-16)}$$

where

- u the windspeed (*m/s*) at the height *h*,
- u_0 is the surface windspeed (*m/s*), as provided by the weather data and usually represents a 10-m election above ground level,
- h' is a reference height of 10 m, which is fixed in the code, and
- p is a dimensionless parameter that varies with stability class and surface roughness as shown in Table 2-3.

Because the maximum intended value of h in Equation (2-16) is 200 m, MACCS assumes that windspeeds higher than 200 m are uniform. While Table 2-3 shows values for both urban and rural surfaces, MACCS only uses p values based on rural surfaces, which are fixed in the code.

Table 2-3 Estimates of the Exponent p in Equation (2-16) for Six Stability Classes and Two Surface Roughnesses (Hanna, Briggs, & Hosker, 1982)

Stability Class	A	B	C	D	E	F
Urban Surfaces	0.15	0.15	0.20	0.25	0.40	0.60
Rural Surfaces	0.07	0.07	0.10	0.15	0.35	0.55

To calculate the final plume height $\Delta h_f(\overline{u})$ in Equations (2-8), (2-9), (2-10), or (2-12), MACCS calculates an average value of u in three steps:

(1). MACCS first makes a first-order estimate of the final centerline height h_f just using the surface windspeed u_0 and the equation for Δh_f, that is, $h_{f,1} = h_0 + \Delta h_f(u_0)$ where h_0 is the initial release height of the plume segment (PLHITE).

(2). Then MACCS calculates the windspeed u_1 at the height $h_{f,1}$ using Equation (2-16).

(3). Finally, MACCS estimates an average windspeed $\overline{u}$ over this range by averaging u_0 and u_1 [i.e., $(u_0 + u_1)/2$], which are the windspeeds at heights h_0 and $h_{f,1}$.

Using the average windspeed $\overline{u}$ from this process, the MACCS calculates both the plume rise trajectory $\Delta h(x)$ shown in Equation (2-7) and the final plume height $\Delta h_f(u)$ shown in either Equation (2-8), (2-9), (2-10), or (2-12), depending on the stability class and the selected plume rise model.

2.4.2.5 Stability Parameter

The stability parameter, S, is defined as the following:

$$S = \frac{g}{T_a}\left(\frac{\partial T_a}{\partial z} + \frac{g}{c_p}\right) \quad \textbf{(2-17)}$$

where

- g is the acceleration due to gravity (9.8 m/s^2),
- T_a is the ambient temperature (288 K),
- $\partial T_a/\partial z$ is the ambient temperatures lapse rate (K/m),
- C_p is the specific heat of air at constant pressure (1.005 kJ/kg-K), and
- g/C_p is the dry adiabatic lapse rate (0.98 K/100 m)

The midpoint of the temperature lapse rates $\partial T_a / \partial z$ are 0.5 K/100 m for stability class E, and 2.75 K/100 m for stability class F (Regulatory Guide 1.23 [NRC, 2007]). Therefore, the stability parameters S for stability classes E and F are 5.04×10^{-4} s^{-2} and 1.27×10^{-3} s^{-2}, respectively. These values are fixed in the MACCS code.

2.5 Atmospheric Dispersion

During downwind transport (x-direction), atmospheric turbulence causes plume segments to expand laterally (y-direction) and vertically (z-direction) relative to the plume direction. Vertical expansion of the plume is increased by surface roughness and is constrained by the ground and by the temperature structure of the atmosphere (i.e., location of inversion layers). Lateral expansion of the plume may be increased from its centerline trajectory by fluctuations in wind direction called plume meander and is unconstrained along the y-direction.

MACCS models plume dispersion during downwind transport using a straight-line Gaussian plume segment model. Gaussian plume dispersion assumes that during its downwind transport, the air concentration of gas molecules and aerosol particles can be modeled as a random walk that generates a normal distribution. Even though plume segments cannot change direction after they have been released, the gaussian model is useful because it is simple and computationally efficient.

The Gaussian plume equations require two spatially dependent dispersion parameters, $\sigma_y(x)$ and $\sigma_z(x)$, to estimate the atmospheric dispersion. These dispersion parameters are the standard deviations of gaussian distribution in the lateral and vertical directions and thereby determine the shape of the plume. The Gaussian plume equations do not consider dispersion in the downwind x-direction.

For the purpose of calculating lateral and vertical dispersion, MACCS treats the plume segment as being located entirely at its reference location (REFTIM), which is a fixed point along the length of the plume segment specified by the user. As such, MACCS does not calculate a time-varying air concentration at an arbitrary location (x, y, z) during plume passage. Instead, the passage of the reference location is used to calculate the entire time-integrated air concentration $\chi(x, y, z)$.

The user can choose to model the lateral and vertical dispersion parameters either according to a power-law model or based on user-supplied lookup tables, both of which depend on stability class and downwind distance. As an option to model long-range dispersion, the user can also implement a time-based dispersion model for lateral dispersion after a specified distance downwind.

2.5.1 Gaussian Plume Equations

The Gaussian plume equations describe the lateral and vertical profile of a plume segment. MACCS assumes that the dispersion of the plume forms a normal distribution in both of these directions, where the lateral dispersion parameter (σ_y) defines the shape in the crosswind direction and the vertical dispersion parameter (σ_z) defines the shape in the vertical direction. When not constrained by the ground or by inversion layers, the Gaussian plume equation has the following form (Turner, 1970):

$$\chi(x,y,z) = \frac{Q}{u} \cdot f_G(y) \cdot f_G(z-h)$$

$$\chi(x,y,z) = \frac{Q}{u} \cdot \frac{1}{\sqrt{2\pi}\sigma_y(x)} exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y(x)}\right)^2\right] \cdot \frac{1}{\sqrt{2\pi}\sigma_z(x)} exp\left[-\frac{1}{2}\left(\frac{z-h}{\sigma_z(x)}\right)^2\right] \quad \textbf{(2-18)}$$

Where

- $\chi(x,y,z)$ is the time-integrated air concentration ($Bq{\cdot}s/m^3$) at downwind location (x,y,z),
- Q is the activity (Bq) entering the spatial element. The released activity Q_0 for a plume segment is the product of RELFRC and CORINV, modified by CORSCA,
- u is the windspeed (m/s), as given by the weather data,
- $f_G(y)$ is the Gaussian distribution (m^{-1}) representing lateral dispersion,
- $f_G(z-h)$ is the Gaussian distribution (m^{-1}) representing vertical dispersion, with a centerline height h,
- h is the height of the plume centerline (m), as determined by the plume rise equations discussed in Section 2.4.2.
- $\sigma_y(x)$ is the lateral dispersion parameter representing one standard deviation of the Gaussian distribution (m), and
- $\sigma_z(x)$ is the vertical dispersion parameter representing one standard deviation of the Gaussian distribution (m).

The lateral and vertical dispersion parameters (σ_y and σ_z) are calculated by the user-selected dispersion rate model, discussed in Section 2.5.3. MACCS does not use Equation (2-18) because it allows for infinite expansion in the vertical direction. Instead, MACCS replaces the boundless Gaussian distribution in the vertical direction with a distribution that is constrained by the ground and the capping inversion layer, as shown in Equation (2-19):

$$\chi(x,y,z) = \frac{Q}{u} \cdot f_G(y) \cdot \psi(z) \qquad \text{for } z \in [0,H] \quad \textbf{(2-19)}$$

and where

- $\psi(z)$ is a vertical distribution (m^{-1}) of the plume segment discussed below,
- H is the height (m) of the capping inversion layer (i.e., the height of the mixing layer), and
- Q, u, and $f_G(y)$ are the same as before.

At short distances, MACCS treats the vertical distribution $\psi(z)$ as being a Gaussian distribution, but accounts for the ground and the inversion layer as vertically bounding by treating them as reflecting boundaries. In this case, MACCS approximates the Gaussian distribution (m^{-1}) in the vertical direction between $[0, H]$ using the following equation:

$$\psi(z) = \frac{1}{\sqrt{2\pi}\sigma_z} \sum_{n=-100}^{100} \left\{ exp\left[-\frac{1}{2}\left(\frac{z-h+2nH}{\sigma_z}\right)^2\right] + exp\left[-\frac{1}{2}\left(\frac{z+h+2nH}{\sigma_z}\right)^2\right] \right\} \quad \textbf{(2-20)}$$

MACCS uses the summation from -100 to +100 to approximate infinite reflections. MACCS uses Equation (2-20) from the time of release until the plume segment is well-mixed between the ground and inversion layer (i.e., uniform in the vertical direction). Once the plume segment is well-mixed, MACCS has the vertical distribution $\psi(z)$ transition from Equation (2-20) to a uniform distribution:

$$\psi(z) = \frac{1}{H} \quad \text{for} \quad z \in [0, H] \quad \textbf{(2-21)}$$

MACCS assumes deposition to the ground does not affect the shape of either vertical distribution. At each radial interval along the plume's trajectory, MACCS tests for a well-mixed vertical distribution according to $\frac{H}{\sigma_z} < 0.03$. This criterion occurs when Equations (2-20) and (2-21) agree to within approximately 1%. When this criterion is met, MACCS switches the vertical distribution $\psi(z)$ from Equation (2-20) to Equation (2-21). Because Equation (2-21) is independent of σ_z, MACCS ceases to calculate σ_z after this transition.

In Section 2.7.2, MACCS uses Equation (2-19) to calculate dry deposition. In Section 2.8, MACCS uses Equation (2-19) to calculate the time-integrated centerline air concentrations $\chi(z = \bar{h})_j$ and ground-level air concentration $\chi(z = 0)_j$ for radial interval *j*. See these sections for more information.

2.5.2 Dispersion Data

The rate at which materials disperse in the atmosphere depends strongly on atmospheric turbulence, which varies on stability class. Pasquill suggested curves for height and angular spread according to stability classes and extrapolated this information to 100 km. Gifford used these data to develop dispersion parameter curves with downwind distance for each stability class (Turner, 1970). As modified, these curves are presented in Figure 2-3 (Gifford F. A., 1976).

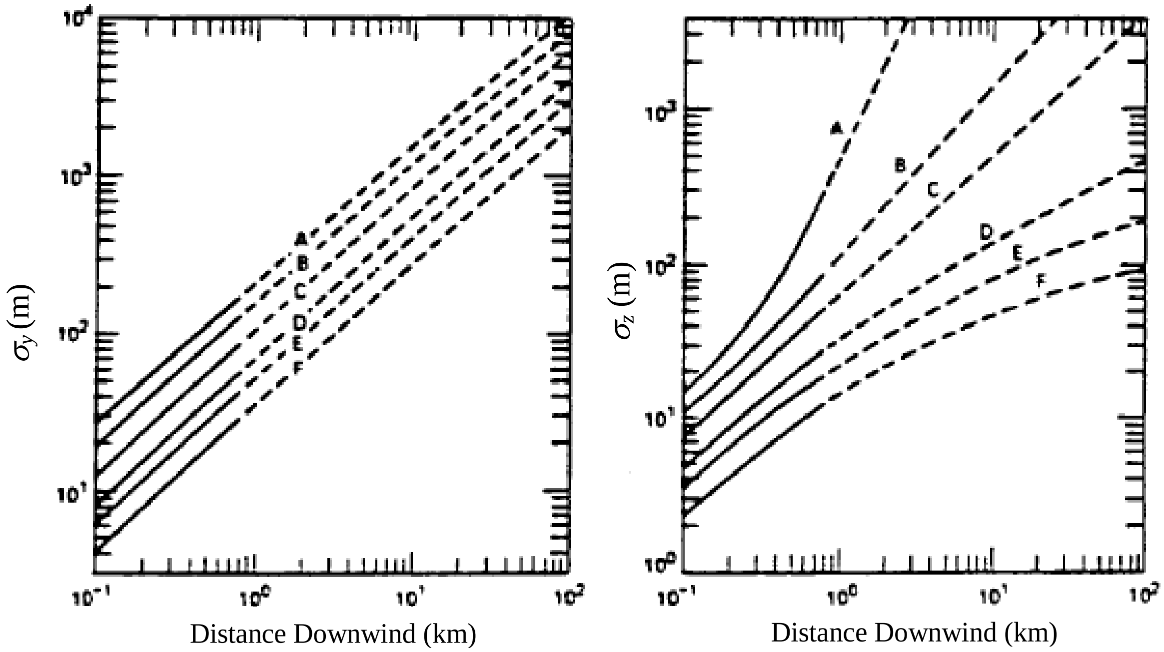

Figure 2-3 Dependence of σ_y and σ_z on Distance for the Six Pasquill-Gifford Stability Classes (A Through F)

The solid lines in Figure 2-3 depict the range of the experimental data; dashed lines are extrapolations. Several other field studies have been conducted to develop dispersion parameter systems. These include studies at Brookhaven (Singer & Smith, 1966), St. Louis (McElroy & Pooler, 1968), and Julich Nuclear Research Center in Germany (Vogt, 1977; Bundesminister des Innern, 1981; Geiss, 1982; Kiefer et al., 1979). Dispersion parameter systems from these field studies are discussed in Section 2.3.3.2 of Till & Meyer (1983).

In the early 1990's, the U.S. Nuclear Regulatory Commission and the Commission of European Communities (CEC) conducted a series of expert elicitations to obtain distributions for uncertain variables used in health consequence analyses related to accidental release of nuclear material. Harper et al. (1995) document the expert elicitation that provides a technical basis for defining the plume lateral and vertical dispersion for a range of stability conditions, a range of surface roughness corresponding to several land-use categories, and downwind distances ranging from 500 m to 30 km.

2.5.3 Dispersion Rate Models

The dispersion parameters σ_y and σ_z in the Gaussian plume equations are important values that determine how quickly the plume disperses as it travels downwind. MACCS has two main methods to determine σ_y and σ_z. The user can choose either a power-law function or user-supplied lookup tables to model the dispersion parameters, both of which depend on distance and stability class. In addition, as an option for modeling long-range dispersion the user can switch the lateral dispersion rate from distance-based dispersion $\sigma_y(x)$ to time-based dispersion $\sigma_y(t)$ at a specified distance downwind.

In addition to the dispersion rate models, linear scaling factors for dispersion (YSCALE, ZSCALE) discussed in Section 2.5.5 and the plume meander models (PLMMOD) discussed in Section 2.5.6 can also affect dispersion.

The rate at which materials disperse in the atmosphere depends strongly on atmospheric turbulence, which varies greatly with stability class. To update the dispersion rate model based on new atmospheric conditions, to account for the initial dispersion from a building wake, and to switch from distance- to time-based dispersion, MACCS uses a concept known as a "virtual source location" described in Section 2.5.4.

2.5.3.1 Power Law Option

The user can choose to use the power-law function by setting a value of zero to the number of distances defined in the lookup table option (NUM_DIST). The dispersion parameter power-law functions for σ_y and σ_z have the following forms:

$$\sigma_{yi}(x) = a_{yi} \cdot \left(\frac{x}{x_0}\right)^{b_{yi}}$$
$$\sigma_{zi}(x) = a_{zi} \cdot \left(\frac{x}{x_0}\right)^{b_{zi}} \qquad \textbf{(2-22)}$$

Where

- σ_{yi} is the lateral dispersion parameter for stability class, *i*, for stability classes A-F. This parameter is the standard deviation of a Gaussian distribution (*m*).
- σ_{zi} is the vertical dispersion parameter for stability class, *i*. This parameter is the standard deviation of a Gaussian distribution (*m*).
- x is the downwind distance (*m*) from the virtual source.
- x_0 is a fixed unit of length, 1 m, and ensures that the term x/x_0 is dimensionless.
- a_{yi} and a_{zi} are the linear coefficients (*m*) in the power-law expressions for lateral dispersion and vertical dispersion, respectively, for stability class, *i*. These values are specified by the input parameters CYSIGA and CZSIGA, respectively.
- b_{yi} and b_{zi} are the exponentials (dimensionless) in the power-law expressions for lateral dispersion and vertical dispersion, respectively, for stability class, *i*. These values are specified by the input parameters CZSIGB and CZSIGB, respectively.

Tadmor & Gur (1969) constructed power-law fits to the Pasquill-Gifford (P-G) curves discussed in Section 2.5.2. NUREG-1150 and the original MACCS Sample Problem A (NRC, 1990, Appendix A) used these values, which are provided in Table 2-4.

Table 2-4 Tadmor and Gur Dispersion Coefficients for Equation (2-22) for a distance range of 0.5 to 5 km.

Stability Class		σ_{yi}		σ_{zi}	
P-G	i	a_{yi}	b_{yi}	a_{zi}	b_{zi}
A	1	0.3658	0.9031	0.00025	2.125
B	2	0.2751	0.9031	0.0019	1.6021
C	3	0.2089	0.9031	0.2	0.8543
D	4	0.1474	0.9031	0.3	0.6532
E	5	0.1046	0.9031	0.4	0.6021
F	6	0.0722	0.9031	0.2	0.6020

*The values of these constants reflect correction of typographical errors identified by Dobbins (1979).

More recently, NUREG/CR-7161 (Bixler, Clauss, & Morrow, 2013) constructed power-law fits to dispersion data from the NRC / CEC joint expert elicitation (Harper, et al., 1995). The SOARCA project (NUREG-1935; NRC, 2012) used these values, which are provided in Table 2-5:

Table 2-5 NUREG/CR-7161 Dispersion Coefficients for Equation (2-22), Median Values of Expert Elicitation (Bixler, Clauss, & Morrow, 2013)[7]

Stability Class		σ_{yi}		σ_{zi}	
P-G	i	a_{yi}	b_{yi}	a_{zi}	b_{zi}
A	1	0.7507	0.866	0.0361	1.277
B	2	0.7507	0.866	0.0361	1.277
C	3	0.4063	0.865	0.2036	0.859
D	4	0.2779	0.881	0.2636	0.751
E	5	0.2158	0.866	0.2463	0.619
F	6	0.2158	0.866	0.2463	0.619

[7] Note that the same parameter values are assigned for classes A/B and for classes E/F. Use of the NUREG/CR-7161 correlations would appear to result in effectively four stability classes: unstable (A/B), slightly unstable (C), neutral (D), and stable (E/F/G).

2.5.3.2 Lookup Table Option

The lookup table option allows the user to define a lookup table as an alternative to power-law functions for σ_y and σ_z. If tracer experiments are available for a site, it may be possible to process the data into tables of lateral and vertical standard deviations (σ_y and σ_z) in this way.

To use the lookup table option, the user sets a value for the number of distances to be defined in the lookup table (NUM_DIST) between 3 and 50. The table requires user-defined distances and dispersion values. This includes lateral and vertical dispersion values (σ_y and σ_z) for each stability class (A to F), for a total of twelve dispersion values at each specified distance.

The lookup table option uses an interpolation technique known as a Hermite cubic spline as discussed by Kahaner, Moler, & Nash (1989). This approach avoids the numerical instabilities observed with other cubic spline fits. The lookup table option does not extrapolate beyond the user supplied distances, and instead simply uses the dispersion value of the closest distance that is specified in the table.

2.5.3.3 Time-Based Option

As an option for modeling long-range dispersion, the user can switch the lateral dispersion parameter from distance-based dispersion $\sigma_y(x)$ (according to the power law equation or the lookup tables previously discussed), to time-based dispersion $\sigma_y(t)$ at a certain distance downwind. The user can choose the time-based dispersion model by setting a value of "LRTIME" to the parameter DISPMD. To only use the distance-based dispersion (either power law option or the lookup-table option), the user sets a value of "LRDIST" for the parameter DISPMD. When mapping dispersion onto the spatial grid, a time-based dispersion model updates dispersion when a change in windspeed occurs, whereas a distance-based dispersion updates dispersion when a change in stability class occurs.

Time-based dispersion requires the user to select the downwind distance at which the code switches from distance-based dispersion to time-based dispersion (CYDIST). The user must also select a linear coefficient, a_c, for the time-based dispersion model (CYCOEF). The default value for the time-based linear coefficient and the transition distance are 0.5 m/s and 30 km, respectively, based on a recommendation by Hanna (2002). The virtual source concept (as discussed in Section 2.5.4) is used to ensure that there is no discontinuity in switching from distance- to time-based dispersion.

When the user implements power law option at close distances, the following equation describes the switch from distance-based dispersion to time-based dispersion:

$$\sigma_y = \begin{cases} a\left(\frac{x}{x_0}\right)^b & x < x_c \\ a_c t & x \geq x_c \end{cases} \quad \textbf{(2-23)}$$

Where

- σ_y is the lateral dispersion parameter (m) in the crosswind direction,

- a is the linear coefficient (m) for distance-based lateral dispersion for a given stability class,

- b is the exponent (dimensionless) for distance-based lateral dispersion for a given stability class,

- a_c is the linear coefficient for time-based lateral dispersion (m/s), specified by the input parameter CYCOEF,

- x_0 is unity (m) used to make the term x/x_0 dimensionless,

- x_c is the distance from the source (m) at which the use of the lateral dispersion model switches from distance- to time-based, specified by the input parameter CYDIST,

- x is the downwind distance from the virtual source (m), and

- t is the time since the plume was released from the virtual source (s).

Alternatively, the user can implement a lookup table for distances less than CYDIST.

When the time-based dispersion model is enabled, time-based dispersion is implemented at distances greater than or equal to x_c as shown in Equation (2-23). However, distance-based dispersion is always applied within the first ring, regardless of the value of CYDIST.

Hanna (2002) recommends that dispersion beyond 30 km be based on time rather than distance. The time-based dispersion option allows the user to implement Hanna's recommendation, and the time-based dispersion model is closer to the treatment used in some Gaussian puff codes. The basis for the recommended distance, 30 km, is that the expert elicitation only considered distances as far as 30 km (Harper, et al., 1995) and that several Gaussian puff codes switch to time-based dispersion at about 30 or 40 km (Draxler & Hess, 1997). The distances required to model consequences for a nuclear reactor accident can extend considerably farther than 30 km, a minimum of 80 km.

2.5.4 Virtual Source Calculation

The dispersion rate models use a concept known as a "virtual" source location. A virtual source location is a release point at a hypothetical upwind location. The location of this virtual source depends on the dispersion rate model and is based on the dispersion at a specific plume location. With these boundary conditions, the dispersion rate models can calculate downwind lateral dispersion (σ_y) and vertical dispersion (σ_z) according to the downwind distance (x; or release time [t]) from the virtual source location. The downwind distance (x) and release time (t) from the virtual source location are used only to calculate downwind dispersion. Plume locations are always expressed relative to the release point, which is the center point of the polar-coordinate computational grid. The virtual source location is generally different for σ_y and σ_z.

MACCS uses these boundary conditions and the associated virtual source location for several different purposes. One purpose is to update dispersion based on changing atmospheric conditions.

The distance-based dispersion parameters $\sigma_y(x)$ and $\sigma_z(x)$ depend on stability class, and the stability class changes discretely as the plume travels downwind. As such, MACCS allows the rate of plume expansion to also change discretely according to the updated atmospheric conditions, in a piecewise continuous fashion.

In order to maintain the correct amount of plume dispersion when changing from one set of atmospheric conditions to the next, MACCS calculates a new virtual source location. See Figure 2-4 for a representation of this piecewise continuous dispersion of the plume.

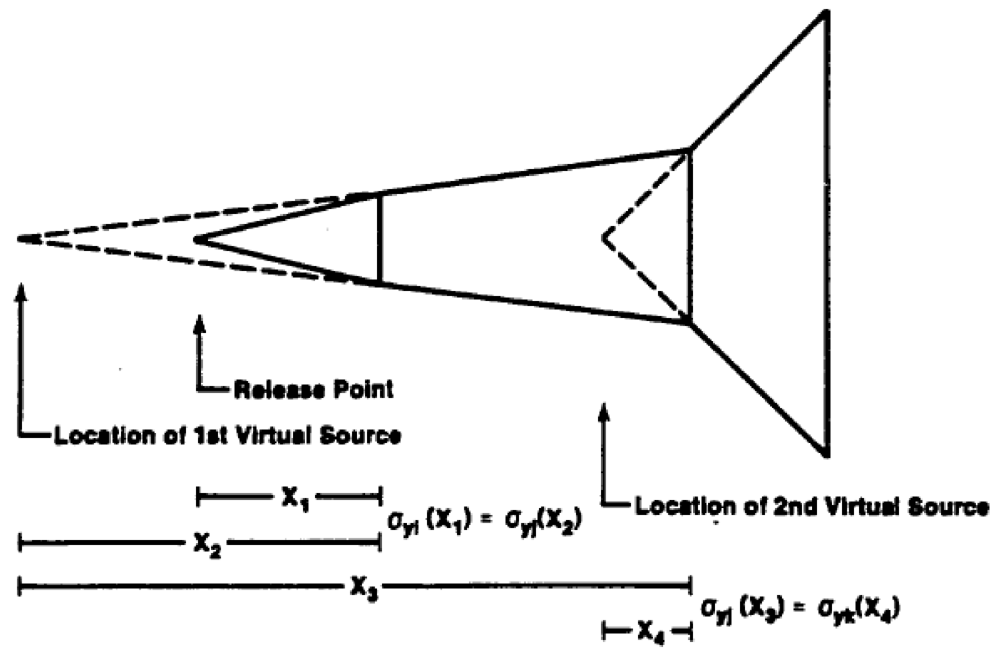

Figure 2-4 Growth of σ_y During Three Time Periods Characterized by Different Atmospheric Stabilities *i, j,* and *k*

MACCS also uses the virtual source location concept to estimate dispersion after building wake effects from the initial release. The initial plume height (SIGZINIT) and plume width (SIGYINIT) caused by building wake are user inputs. These initial plume dimensions at a downwind distance of zero meters act as the boundary conditions for calculating the virtual source location.

Another example of where MACCS uses a virtual source term is to switch from a distance-based dispersion parameter $\sigma_y(x)$ to time-based dispersion $\sigma_y(t)$. Like the changes in atmospheric conditions, the switch to time-based dispersion is a discrete change. The boundary condition for the virtual source location is the specific amount of plume dispersion (previously determined by one of the distance-based dispersion models) at a user specified downwind location (CYDIST). From this boundary condition, the time-based dispersion model calculates downwind dispersion based on the time (t) relative to the time it was released from the virtual source. Lateral dispersion $\sigma_y(t)$ does not depend on the stability class, and so after a switch to time-based dispersion, the virtual source time is constant. Note, however, that time-based dispersion is not constant with distance when there are changes in windspeed. Therefore, the plume shape over the spatial grid can appear to have discrete changes like those shown in Figure 2-4, although for a different reason.

The following shows how MACCS uses the power law option for calculating the new source distances (i.e., the downwind distances from the virtual source) based on a change in stability class. Let *i* be the stability class before the change in atmospheric conditions and x_{yi} and x_{zi} be the source distances under the original conditions (i.e., the downwind distances to the virtual source just before the stability class changes). Let *j* be the stability class after the change, and x_{yj} and x_{zj} be the virtual source distances under the updated conditions. To ensure continuity, σ_{yi} must be equal to σ_{yj} and σ_{zi} must be equal to σ_{zj} at the transition. Thus,

$$\begin{aligned} a_i\left(x_{y_i}\right)^{b_i} &= \sigma_{y_i} = \sigma_{y_j} = a_j\left(x_{y_j}\right)^{b_j} \\ c_i\left(x_{z_i}\right)^{d_i} &= \sigma_{z_i} = \sigma_{z_j} = c_j\left(x_{z_j}\right)^{d_j} \end{aligned} \tag{2-24}$$

These equations can be solved explicitly for the new virtual source distance to produce the following result:

$$\begin{aligned} x_{y_j} &= \left(\frac{\sigma_{y_i}}{a_j}\right)^{\frac{1}{b_j}} = \left[\frac{1}{a_j} a_i\left(x_{y_i}\right)^{b_i}\right]^{\frac{1}{b_j}} \\ x_{z_j} &= \left(\frac{\sigma_{z_i}}{c_j}\right)^{\frac{1}{d_j}} = \left[\frac{1}{c_j} c_i\left(x_{z_i}\right)^{d_i}\right]^{\frac{1}{d_j}} \end{aligned} \tag{2-25}$$

This same approach can be used in conjunction with the lookup table option described above. For this option, calculating the virtual source distances and the dispersion parameter values use the same lookup tables and interpolation methods. The ability to calculate the virtual source distance assumes that the inverse functional dependence for the lookup table can be evaluated, i.e., that given a dispersion value, a unique value of *x* can be determined. To ensure uniqueness, MACCS requires the tables to have monotonically increasing values.

2.5.5 Dispersion Scaling Factors

MACCS has scaling factors that act as multipliers on σ_y and σ_z. The user can change the lateral scaling factor (YSCALE) to linearly decrease or increase the amount of lateral plume dispersion (σ_y), and likewise can change vertical scaling factor (ZSCALE) to linearly decrease or increase the amount of vertical plume dispersion (σ_z).

These scaling factors can help account for phenomena that would tend to increase or decrease the plume dimensions. Two such phenomena that are commonly included in plume modeling are plume broadening caused by meander (wind direction fluctuations) and increased vertical spreading caused by the surface roughness of terrain. MACCS has separate models for plume meander, as described in Section 2.5.6. As such, the lateral scaling factor is usually set to 1.0.

However, MACCS does not contain a separate model to account for surface roughness, so users commonly modify the vertical scale factor for each site.

The surface roughness of terrain causes increased turbulence and increased vertical dispersion. The dispersion rate model data are from field experiments (e.g., Prairie Grass experiment) or other sources with an associated surface roughness. However, the terrain near nuclear power plants typically have a greater surface roughness length than those for field experiments and therefore have more vertical dispersion. Hanna, Briggs, & Hosker (1982, p. 29) estimates that the increase in vertical dispersion is proportional to the surface roughness with an exponential factor of “q,” where the exponent q is a constant that is typically a value of 0.2, but can range from 0.10 to 2.5. As such, users usually account for the increased amount of vertical dispersion by calculating a value for ZSCALE based on the following relationship:

$$ZSCALE = \left(\frac{z_0}{z_{0,ref}}\right)^q = \left(\frac{z_0}{3\ cm}\right)^{0.2} \tag{2-26}$$

Where

- ZSCALE is the linear scaling coefficient for vertical dispersion.
- $z_{0,ref}$ is a reference surface roughness. This should be the surface roughness associated with the data underlying the dispersion rate model, which is 3 cm if the data are from the Prairie Grass experiments.
- z_0 is the surface roughness (cm) of the terrain within a few kilometers of the release.
- q is an exponential factor that relates surface roughness to vertical dispersion, typically a value of 0.2.

Figure 2-5 presents some approximate surface roughness lengths for different land uses based on the values in (Lettau, 1969; Briggs, 1984; Randerson, 1984).

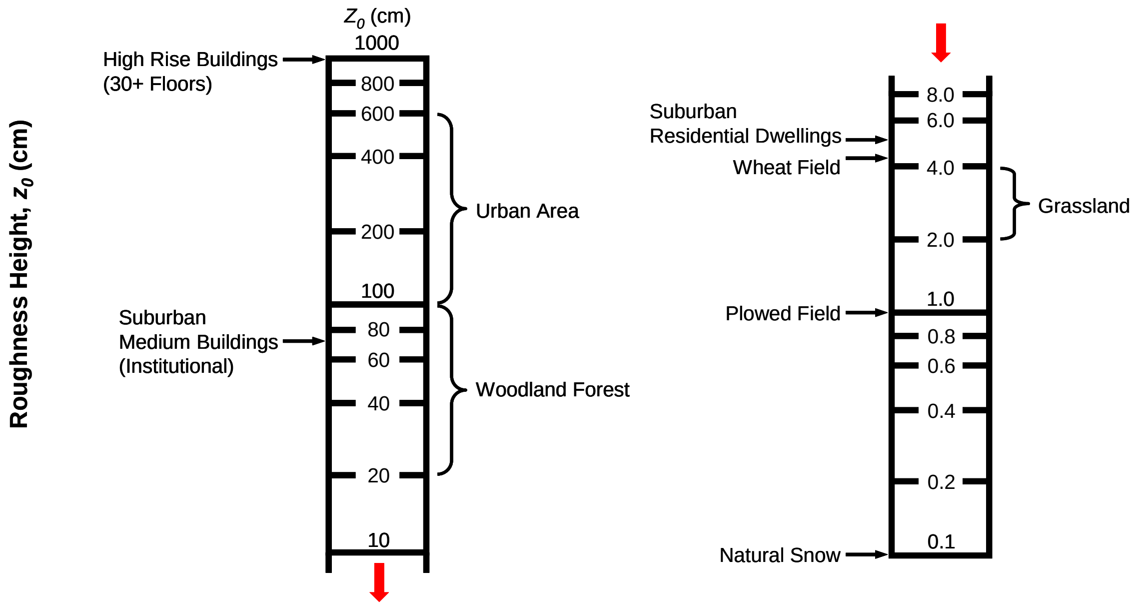

Figure 2-5 Approximate Surface Roughness Lengths (z_0) for Various Surfaces

Because surface roughness affects both vertical dispersion and dry deposition velocities, users should choose values for ZSCALE and VDEPOS that are consistent. Dry deposition velocity is discussed in more detail in Section 2.7.2

2.5.6 Plume Meander

Wind shifts that can occur at time intervals less than that of the recorded weather data (i.e., less than the weather averaging time) can result in an apparent dispersion that is greater than would be computed using dispersion curves based on measurements over a shorter time period, such as the Pasquill-Gifford curves. The apparent increase in lateral dispersion can be significant under stable, low-wind speed conditions. This effect is known as plume meander.

MACCS has two explicit models for plume meander, which are the original MACCS model and a model based on NUREG/CR-2260 (Snell & Jubach, 1981) and Reg Guide 1.145 (NRC, 1983). A user can choose not to use a plume meander model by giving a value of "OFF" to the parameter MNDMOD. Even with no explicit model for plume meander, the user can still account for increased lateral dispersion using a constant, linear scaling factor (YSCALE), as discussed in Section 2.5.5.

The MACCS plume meander models calculate a meander factor. Like the lateral dispersion scaling factor, YSCALE, the meander factor acts as a multiplier on lateral dispersion (σ_y) and works with either distance-based or time-based dispersion rate models.

$$\sigma_{ym} = f_m \cdot \sigma_y \quad \textbf{(2-27)}$$

Where

- σ_{ym} is lateral dispersion (m) accounting for plume meander,

- σ_y is lateral dispersion (m) not accounting for plume meander,
- f_m is the meander factor (dimensionless), as calculated by one of the MACCS plume meander models described below.

Lateral dispersion, σ_y, is based on one of the dispersion rate model previously described, either distance-based $\sigma_y(x)$ defined in terms of a power-law equation or as a lookup table, or it can be time-based $\sigma_y(t)$. Depending on the meander model, the meander factor f_m can depend either on release duration or on downwind distance, windspeed, and stability class.

2.5.6.1 Original Plume Meander Model

A user can choose to use the original MACCS plume meander model by setting a value of "OLD" to the parameter MNDMOD. The original MACCS model was designed based on the Pasquill-Gifford dispersion data and accounts for the effect of meander during transport of a plume segment using a meander factor, as defined in Equation (2-27). The meander factor in the original meander model is defined as follows:

$$f_m = \begin{cases} 1 & \Delta t_{release} \leq \Delta t_0 \\ (\Delta t_{release}/\Delta t_0)^{F_1} \quad if & \Delta t_0 < \Delta t_{release} \leq \Delta t_1 \\ (\Delta t_{release}/\Delta t_0)^{F_2} & \Delta t_1 < \Delta t_{release} \leq 10 \end{cases} \tag{2-28}$$

Where

- $\Delta t_{release}$ is the release duration for the plume segment (s), specified in the parameter PLUDUR,
- Δt_0 is the release duration (s), defined by the parameter TIMBAS. This is usually chosen to be 600 s, which is the release duration of the Prairie Grass experiment,[8]
- Δt_1 is the breakpoint in release duration (s), defined by the parameter BRKPNT,
- F_1 is the exponent for time dependence below the breakpoint (dimensionless), defined by the parameter XPFAC1, and
- F_2 is the exponent for time dependence above the breakpoint (dimensionless), defined by the parameter XPFAC2.

All the values used to define the meander factor are input parameters. Gifford (1975) recommends a value of 0.2 for F_1 and a value of 0.25 for F_2 when the breakpoint is 3,600 seconds. Users should limit plume segment release durations to 10 hr, because Equation (2-28) is not intended to be used

[8] There is some controversy over the correct reference time, Δt_0, to use in the denominator of Equation (2-26). The averaging time for the Prairie Grass tests was 600 s and some authors support using this value; other authors support using a value of 180 s. Since the reference time in Equation (2-26) is a user input (TIMBAS), either value can be chosen by the user.

for longer release durations. If a plume segment exceeds 10 hr a nonfatal warning is given in the output file and the meander factor is calculated as though the plume duration were 10 hr.

2.5.6.2 New Plume Meander Model (Based on Regulatory Guide 1.145)

MACCS contains a plume meander model based on the meander factors developed in NUREG/CR-2260 (Snell & Jubach, 1981), which in turn is based on the Rancho Seco field tracer experiments (Start, et al., 1977). NUREG/CR-2260 supports Regulatory Guide 1.145 (NRC, 1982). A user can choose to use this meander model by setting a value of "NEW" to the parameter MNDMOD.

The NUREG/CR-2260 meander factors correct the Pasquill-Gifford lateral dispersion values to account for plume meander. Unlike the original model, this model accounts for the observation that plume meander depends on stability class and windspeed. NUREG/CR-2260 states that plume meander is most prevalent for stability classes D through G for low wind speeds. As such, the authors assigned a range of windspeeds for which plume meander is applicable, that being fully applicable below 2 m/s, not applicable above 6 m/s, and between these two values a meander factor that varies logarithmically with windspeed. Furthermore, because the tracer field experiments used sensors out to 800 m, NUREG/CR-2260 deemed it inappropriate to model additional meander beyond this point. MACCS generalizes the approach and defines the meander factor as follows:

$$f_m = \begin{cases} m_i \cdot f(u) & x \le d \\ 1 & x > d \end{cases} \qquad \textbf{(2-29)}$$

And

$$f(u) = \begin{cases} 1 & u \le u_1 \\ \dfrac{1}{m_i} \cdot exp\left[\left(1 - \dfrac{ln(u) - ln(u_1)}{ln(u_2) - ln(u_1)}\right) \cdot ln(m_i)\right] & u_1 < u \le u_2 \\ 1/m_i & u_2 < u \end{cases} \qquad \textbf{(2-30)}$$

Where

- m_i is the maximum meander factor (dimensionless) for stability class, i. These values are specified by the input parameter MNDFAC$_i$, and where integers of i = 1, 2, 3, 4, 5, and 6 correspond to stability classes A, B, C, D, E, and F/G, respectively.
- x is the downwind distance from the virtual source (m).
- d is a distance within which plume meander affects lateral plume dispersion, as defined by the parameter MNDIST.
- $f(u)$ is a dimensionless function that ranges between $(1/m_i, 1)$ and specifies how quickly the meander factor diminishes as windspeed increases.
- u is windspeed (m/s), according to the weather data.

- u_1 is the windspeed (m/s) where the meander factor changes from a constant value to a decreasing function of the windspeed, as defined by the parameter WINSP1.

- u_2 is the windspeed (m/s) where the meander factor reaches one for all stability classes, as defined by parameter WINSP2.

As indicated in Equation (2-29), this meander model treats meander for distances less than d, but does not treat additional meander beyond d. To ensure continuity in dispersion at d, MACCS uses the virtual source location method described in Section 2.5.4. The MACCS plume meander model closely matches the Regulatory Guide 1.145 model when the meander factor m_i = [1, 1, 1, 2, 3, 4] for stability class i, u_1 = 2 m/s, u_2 = 6 m/s, and d = 800 m. These are the recommended meander factors for MNDFAC$_i$.

Analysts should be aware that these meander factors were derived based as corrections for Pasquill-Gifford lateral dispersion values, which were based on vertical temperature lapse rates to characterize atmospheric releases and based on 1-hour releases. Analysts should use caution when using this model with other dispersion curves or other stability classification methods. In addition, while the original plume meander model in MACCS accounts for the duration of the release, the Regulatory Guide 1.145 model is calibrated for 1-hour release durations. This plume meander model overpredicts peak doses for release durations significantly longer than 1 hour and underpredicts peak doses for release durations significantly shorter than 1 hour. Enforcement of this model restriction is left to the user; MACCS does not restrict the duration of plume segments to be approximately 1 hour when this model is selected.

2.6 Downwind Transport

The length of a plume segment depends on its release duration (PLUDUR) and the windspeed during release. For plume segments that span multiple hours of weather data, MACCS matches the plume segment release period with the weather data. As such, a plume segment length L_s is defined by the following:

$$L_s = \sum_{i=n}^{N} u_i \cdot \Delta t_{r,i} \tag{2-31}$$

where

- L_s is the length (*m*) plume segment,

- u_i (*m/s*) is the windspeed during time period i, as given by the weather data,

- $\Delta t_{r,i}$ (*s*) is the duration of release during weather hour *i*, where the summation of all durations is equal to the full release duration of the plume segment, PLUDUR.

- {*n*, ..., *N*} is the set of weather hours during which release occurs, where the delay to plume segment release (PDELAY) is in hour *n*, and where plume segment release ends (PDELAY + PLUDUR) in hour *N*.

The values of $\Delta t_{r,n+1}$ through $\Delta t_{r,N-1}$ are all equal to one hour and $\Delta t_{r,n}$ and $\Delta t_{r,N}$ may be parts of an hour, assuming that weather data are hourly. The MACCS downwind plume segment transport does not consider how the height of the plume affects the windspeed (i.e., no vertical wind shear). Likewise, the Gaussian equations in MACCS assume that turbulent velocities are small compared with the mean windspeed (Kao, 1984). Therefore, the plume segment moves downwind as one unit with a distinct cutoff at the leading and trailing edge.

After the plume segment is fully released, it continues to change speeds according to the windspeed values specified in the weather data. Changes in windspeed simultaneously affect the entire plume segment. Therefore, the length of the plume segment is constant during downwind transport (except when a transition from weather sequence data to boundary weather occurs, for which MACCS preserves the residence time of the plume segment overhead rather than the length). As such, MACCS determines the transit time of any location along the plume segment (e.g., head, midpoint, tail) to any downwind grid point (e.g., inner boundary, midpoint, or outer boundary of a radial interval) with the following equation:

$$t_d = \sum_{i=m}^{M} \Delta t_{d,i} \tag{2-32}$$

Where

- t_d is transit time (s) of any point of interest along a plume segment to a downwind location, relative to the release time (PDELAY) of the plume segment's reference location (specified by REFTIM),
- $\Delta t_{d,i}$ is the duration (s) of plume segment transit during weather hour i, and
- $\{m, ..., M\}$ is the set of weather hours during plume segment transit.

As before, the values of $\Delta t_{d,m+1}$ through $\Delta t_{d,M-1}$ are all equal to one hour and $\Delta t_{d,m}$ and $\Delta t_{d,M}$ may be part of an hour. The first duration $\Delta t_{d,m}$ is the remaining time in weather hour m at the time specified by PDELAY. The last duration $\Delta t_{d,M}$ is based on the windspeed u during weather hour M and the remaining distance of the point of interest on the plume segment to the downwind location, $\frac{(d_M - d_{M-1})}{u_M}$, where d_M is the distance to the downwind location from the point of release.

Finally, the plume segment overhead time, Δt_e, which is the duration of a plume segment traversing any downwind location is given by the following equation:

$$\Delta t_e = t_t - t_h \tag{2-33}$$

Where t_h and t_t are the arrival times (s) of the head and the tail of the plume segment, respectively. The plume segment overhead time is an input to dose equations for cloudshine and direct inhalation, discussed in more detail in Section 3.

2.7 Plume Depletion

Radioactivity is removed from plume segments by decay and by deposition of radioactive materials onto the ground. While radioactivity reduces plume concentrations, the decay and ingrowth of radionuclides is not considered in the computational framework until after atmospheric transport modeling is complete. Once undecayed air and ground concentrations are known, MACCS adjusts the air and ground concentrations to account for radioactive decay and ingrowth.

Deposition onto the ground is caused by wet and dry deposition onto surfaces. The deposition caused by precipitation is called wet deposition. Deposition not caused by rain is called dry deposition. In MACCS, these processes are modeled as first-order rate processes.

2.7.1 Radioactive Decay and Ingrowth

After atmospheric transport modeling is complete, MACCS adjusts the air and ground concentrations to account for radioactive decay and ingrowth. MACCS accounts for radioactive decay and ingrowth using data in the decay chain definition file INDEXR.DAT. The dataset contains the half-lives, decay products, and decay fractions for 825 radionuclides. The dataset is supplied by the Radiation Shielding Information Center as part of the FGR-DOSE/DLC-167 data package.

MACCS allows decay chains to have up to five decays, which is a total of six generations of nuclides including the parent. Decay chains can be terminated in two ways. If the decay chain reaches a stable isotope, the chain is automatically terminated. The other option is to terminate the decay chain early. To avoid the unnecessary computational expense, this is commonly done when the decay product is very long-lived and contributes very little to the overall dose. The user can terminate a decay chain by adding the long-lived daughter product to the list of “pseudostable” isotopes (NAMSTB).

For example, Cs-135 is formed by beta decay of Xe-135. It decays to Ba-135 by low-energy beta decay with a half-life of 2.3×10^6 years. Because of the long half-life and low energy beta produced by its decay, Ba-135 has little effect on doses and is often included as a decay-chain terminator in MACCS calculations by including it as a pseudostable isotope.

In some older calculations, decay products were treated implicitly by adding the dose coefficients for the progeny to the one for the parent radionuclide and including the progeny in the list of pseudostable radionuclides. This simplification was done to reduce memory and CPU requirements. It works when the half-life for the progeny is much shorter than the one for the parent so that the progeny decays almost immediately once the parent radionuclide decays. This practice somewhat disguises the set of radionuclides that are being treated in a problem and reduces flexibility. Since computer memory is at much less of a premium now than when MACCS was initially developed, this practice of implicitly including progeny in a calculation is not used with the latest dose conversion factor files.

MACCS evaluates the radioactive decay of each radionuclide in the initial inventory and buildup of radioactive daughters using standard formulae (Adamson, 1973, p. 1046). For simple first-order decay with no ingrowth, MACCS uses the following equation:

$$\frac{D(t)}{D_0} = \frac{\lambda N(t)}{\lambda N_0} = e^{-\lambda t} \tag{2-34}$$

Where

- $D(t)$ is the radioactivity (Bq) at time *t*,
- D_0 is the radioactivity (Bq) at time zero,
- $N(t)$ is the number of radioactive atoms at time *t*,
- N_0 is the number of radioactive atoms at time zero, and
- λ is the decay constant (*1/s*), as provided by the data in the decay chain definition file (INDEXR.DAT).

Decay of a parent radionuclide to a radioactive daughter is calculated using the following equation:

$$D_2(t) = \frac{\lambda_2}{\lambda_2 - \lambda_1} D_{1,0}\left(e^{-\lambda_1 t} - e^{-\lambda_2 t}\right) + D_{2,0} e^{-\lambda_2 t} \tag{2-35}$$

Where

- $D_2(t)$ is the activity (*Bq*) of the daughter at time *t*,
- $D_{1,0}$ and $D_{2,0}$ are the activities (*Bq*) of the parent and daughter at time zero, and
- λ_1 and λ_2 are the decay constants (*1/s*) of the parent and daughter ($\lambda_1 \neq \lambda_2$), as provided by the data in the decay chain definition file (INDEXR.DAT).

In Equation (2-35), the second term represents decay of daughter atoms initially present at time zero.

Because the ingrowth of daughter products occurs between accident initiation and plume segment release, there are two options ("PARENT" and "PROGENY") for how to treat radioactive decay using the parameter APLFRC. The "PARENT" option calculates radioactive decay and ingrowth in one step, starting from accident initiation. In this option, MACCS does not consider the ingrowth of daughter products until after transport. The "PROGENY" option calculates radioactive decay and ingrowth in two steps. First, MACCS calculates the decay and ingrowth that occurs between accident initiation and plume segment release, which MACCS uses to update the radionuclide inventory. MACCS then calculates decay and ingrowth as it would have in the "PARENT" option, only in this option radioactive decay and ingrowth start from the intermediate step of plume release.

The two options can produce different results because the daughter products created between accident initiation and plume segment release can have different chemical properties than the parents. For instance, the daughter product may be more volatile and have a larger release fraction, or it may form different aerosol sizes that impact its deposition rate during transport. In the "PARENT" option, the new decay products have the same release fraction and aerosol size distribution as the parent radionuclide, while in the "PROGENY" option, daughter products are treated no differently from the same radionuclides present at accident initiation.

Neither option is perfect, but the better option depends on the fraction of decay that occurs before versus after release from the fuel and whether the decay involves a phase change between parent and progeny. For example, if a radionuclide is formed by decay before being released from the fuel, it is most likely released in proportion to its own chemical group, so "PROGENY" is the better option. If the decay occurs in an aerosol particle after release from fuel, then the decay product is likely to remain bound in the aerosol and to be released in proportion to the "PARENT" chemical group. If a decay product is volatile, as is the case when a noble gas is formed, then the decay product might be released in proportion to its own chemical group or might remain trapped for a period of time in an aerosol and thereby behave like the parent.

MACCS calculates a set of air and ground concentrations independent of decay and ingrowth. For the early phase, ATMOS calculates a separate set of air and ground concentrations for each plume segment. For the intermediate and long-term phases, the sum of the ground concentrations from all plume segments is sufficient.

ATMOS adjusts the concentrations to consider decay and ingrowth starting from the beginning of the accident. For early doses, ATMOS considers decay and ingrowth up to the point in time when a plume segment exits a radial interval, i.e., at the point in time when deposition is complete for the radial interval being reported. This is done for each plume segment, as the timing of the plume segments affect the amount of decay and ingrowth. For exposures that continue after plume departure, the early dose pathways in EARLY continue to account for decay and ingrowth in the dose calculations. For late doses, ATMOS considers decay and ingrowth of the total ground concentration up to the end of the early phase. For exposures that continue after the early phase, the late dose pathways in CHRONC also continue to account for decay and ingrowth.

2.7.2 Dry Deposition

Dry deposition is modeled using Chamberlain's source depletion method (Chamberlain, 1953; Hosker, 1974; Karlsson, 1982) modified to allow treatment of a particle size distribution and of capping of vertical expansion by an inversion layer. The source depletion method calculates the rate at which materials are deposited onto the ground (the deposition flux) as the product of the ground-level air concentration of the materials and the dry deposition velocity (Sehmel, 1984) of those materials. The method neglects the effects of deposition on the vertical distribution of the plume. Thus, dry deposition does not perturb the normal distribution of plume materials in the vertical direction. This is generally an excellent assumption because turbulent advection is generally on the order of 0.5 m/s while deposition velocities are typically a few cm/s or less. When stable conditions occur, the assumption introduces an artificial flux of material from upper regions of the plume to regions near the ground.

The ground-level air concentration at a location (x, y, z = 0) of a plume that is capped by an inversion layer at height H is obtained from Equation (2-19) and setting z = 0, which yields the following:

$$\chi(x, y, 0) = \frac{Q}{u} \cdot f_G(y) \cdot \psi_0 \tag{2-36}$$

Where $\psi(z)$ is the plume distribution in the vertical direction (m^{-1}), as defined in Equations (2-20) and (2-21), and ψ_0 is the value of the distribution at $\psi(z = 0)$. The flux of plume material to the ground, $\omega(x, y)$ is given by the following:

$$\omega(x, y) = v_d \cdot \chi(x, y, 0) \tag{2-37}$$

where v_d, the dry deposition velocity (VDEPOS), embodies the combined effects of gravitational settling, impaction, and diffusion of suspended materials onto the ground and other surfaces (Sehmel, 1984).

The rate of plume material loss (dQ/dx) by dry deposition onto the ground into a differential length *dx* located at the downwind distance *x* is the following (Hosker, 1974):

$$\frac{dQ}{dx} = -\int_{-\infty}^{\infty} \omega(x, y) dy \tag{2-38}$$

Substitution of Equations (2-36) and (2-37) into Equation (2-38) gives,

$$\frac{dQ}{dx} = -\frac{v_d \psi_0 Q}{u} \int_{-\infty}^{\infty} f_G(y)\, dy = -\frac{v_d \psi_0 Q}{u} \tag{2-39}$$

where

- v_d is the dry deposition velocity (*m/s*), as specified by VDEPOS,
- ψ_0 is shorthand for $\psi(z = 0)$, which is the ground-level value of the plume distribution in the vertical direction (m^{-1}), which is defined in Equation (2-20) and (2-21),
- Q is the released activity (*Bq*),
- *u* is the windspeed (*m/s*), as given by the weather data, and
- $f_G(y)$ is the Gaussian distribution (m^{-1}) representing lateral dispersion.

The integral of the lateral Gaussian distribution simplifies to one. During any single hour of weather data, the mean windspeed *u* is constant. Thus *dx* = *udt*, which when substituted into Equation (2-39) gives,

$$\frac{dQ}{dt} = -v_d \cdot \psi_0 \cdot Q \tag{2-40}$$

Rearranging and integrating and assuming ψ_0 is a constant within a given radial interval gives,

$$\frac{Q_1}{Q_0} = f_d = exp\left[-v_d \cdot \psi_0 \cdot \Delta t_{ref}\right] \quad \textbf{(2-41)}$$

where

- Q_0 is the amount of aerosols transported into the radial interval,
- Q_1 is the amount transported out of the radial interval,
- $f_d = Q_1/Q_0$ is the fraction not removed by dry deposition when the plume segment transverses the radial interval,
- Δt_{ref} is the time required for the reference location (REFTIM) of a plume segment to transverse the radial interval, and
- v_d and ψ_0 are the same as previously defined.

In MACCS, the effect of particle size on dry deposition velocity is treated by discretizing the particle size distribution of the materials subject to dry deposition (the radioactive aerosols) into i particle size bins (NPSGRP), specifying the fraction (p_i) of all aerosol materials in each particle size bin (PSDIST), assigning a dry deposition velocity (v_{di}) to each size bin (VDEPOS$_i$), and applying Equation (2-41) separately to each bin. Thus, the fraction f_{di} of particle size bin i not removed by dry deposition when the plume segment transverses the radial interval is the following:

$$\frac{Q_{1i}}{Q_{0i}} = f_{di} = exp\left[-v_{di} \cdot \psi_0 \cdot \Delta t_{ref}\right] \quad \textbf{(2-42)}$$

To calculate Equation (2-42), MACCS must first calculate the ground-level value of the vertical plume profile, ψ_0, and the time Δt_{ref} for the plume segment reference location to transverse the radial interval.

Before the plume is fully vertically dispersed, ψ_0 depends on the vertical dispersion parameter, $\sigma_z(x)$, which in turn depends on the downwind distance [see Equation (2-20)]. For radial interval j, MACCS calculates the vertical dispersion parameter using $\bar{\sigma}_{z,j}$ shown in Equation (2-54), which is an average of the dispersion parameter values at the inner and outer edge of the radial interval. After the plume is fully vertically dispersed, ψ_0 is equal to $1/H$, where H is the mixing layer height [see Equation (2-21)].

The term, Δt_{ref}, is the time of arrival of the segment's reference location at the outer edge of the radial interval minus the time of its arrival at the inner edge of the interval. Because MACCS allows plume segments to have long release durations and radial intervals can have narrow radial dimensions, lengthy plume segments that span more than one radial interval are common. Of course, when exiting a radial interval, even a short plume segment lies over at least two radial intervals. Even when a plume segment lies above more than one radial interval, dry deposition from the segment is assumed to occur entirely onto the radial interval that contains the reference location regardless of how many radial intervals lie under the entire length of the segment.

After a segment has traversed a radial interval, the amounts of material in each particle size bin are decreased by the amounts removed from the bin by dry deposition during transport across the radial interval. Then, the fractions that specify the amounts of aerosol materials in the bins of the aerosol size distribution are recalculated and as a consistency check their sum is renormalized to be one.

Finally, since $Q_1 = \sum_i Q_{1i}$, $Q_{1i} = Q_{0i} \cdot f_{di}$, and $Q_{0i} = Q_0 \cdot p_i$, the fraction (f_d) of all aerosol materials in all of the size bins *i* that remains after dry deposition has occurred from each bin onto the entire radial interval is given by:

$$f_d = \frac{Q_1}{Q_0} = \frac{1}{Q_0}\sum_i Q_{1i} = \frac{1}{Q_0}\sum_i Q_{0i} \cdot f_{di} = \frac{1}{Q_0}\sum_i Q_0 \cdot p_i \cdot f_{di} = \sum_i p_i \cdot f_{di} \tag{2-43}$$

Section 2.8 provides more details on how dry deposition affects air and ground concentrations.

2.7.3 Wet Deposition

The wet deposition model estimates how much material is deposited during episodes of precipitation. Wet deposition is treated as a function of both precipitation duration and intensity. Wet deposition is calculated using the model of Brenk & Vogt (1981):

$$\frac{dQ}{dt} = -\Lambda Q = -C_1\left(\frac{I}{I_0}\right)^{C_2} \cdot Q \tag{2-44}$$

Where

- Q is the amount of suspended radioactive material (*Bq*),
- Λ is the removal rate of aerosols by wet deposition (*1/s*),
- C_1 is the linear wet deposition coefficient (*1/s*), as given by the parameter CWASH1,
- C_2 is the exponential wet deposition coefficient (dimensionless), as given by the parameter CWASH2,
- I is the intensity of precipitation (*mm/hr*), as specified by the weather data, and
- I_0 is the unit rain intensity, 1 mm/hr.

Integrating Equation (2-44), assuming a constant precipitation rate, provides the following equation:

$$\frac{Q_1}{Q_0} = f_w = exp\left[-C_1\left(\frac{I}{I_0}\right)^{C_2} \Delta t_w\right] \tag{2-45}$$

Where

- $f_w = Q_1/Q_0$ is the fraction of suspended aerosols in a plume segment that is not removed by wet deposition while crossing a radial interval,

- Q_0 is the amount of radioactive material (Bq) transported into the radial interval,
- Q_1 is the amount of radioactive material (Bq) transported out of the radial interval,
- Δt_w is the duration (s) that the full plume segment takes to cross both ends of a given radial interval, and
- C_1, C_2, I, and I_0 are the same as previously defined.

Whereas the dry deposition model depends on particle size, the wet deposition model does not. Also, unlike dry deposition, which is a continuous and relatively slow process, wet deposition is discontinuous and often is quite rapid relative to dry deposition. Therefore, treating wet deposition entirely onto the radial interval that lies under the segment's reference location is not acceptable. Instead, wet deposition is apportioned over all the radial intervals that lie under the segment.

For example, consider the release of a plume segment during a 10-hour period during which the average windspeed is 5 m/s. At the end of the release, the plume segment has a length of 180 km, and especially during the early stages of a MACCS calculation, extends over many radial intervals. Suppose the windspeed drops to 1 m/s and that a one-hour rainstorm begins just as the segment's reference location enters a 3.6 km wide radial interval. In this example, most of the content of a 180 km plume segment deposits onto a 3.6 km radial interval. This is clearly unrealistic.

To apportion wet deposition over all the radial intervals traversed wholly or partially by a plume segment during a rainstorm, on an hourly basis, the average fraction of plume segment length f_{av} that lies over a radial interval during the storm must be calculated. Let L_{sj} be the length of the portion of the plume segment that lies over the radial interval j beneath the plume at time t. Figure 2-6 is a plot of L_{sj} vs t for a segment of total length L_S and an interval of radial length L_j (length in the downwind direction), where $L_s \neq L_j$. Because $L_s \neq L_j$, the plot has a trapezoidal shape with height $L_{\max} = \text{Min}(L_s, L_j)$. Note that when $L_s = L_j$ the trapezoid is reduced to a triangle.

In Figure 2-6, t_1 is the time when the head of the plume segment enters the radial interval; t_6 is the time when the tail of the segment leaves the radial interval. If $L_s < L_j$, t_2 is the time when the tail of the segment enters the radial interval and t_4 the time when the head leaves the radial interval; if $L_s > L_j$, t_2 is the time when the head of the segment leaves the radial interval and t_4 is the time when the tail enters the radial interval. The time points, t_3 and t_5, are indicated by vertical dashed lines, denote the beginning and end of a one-hour time period (t_5 - t_3 = 1 hr) during which weather data is constant. Since windspeed has only one value during any hour of weather data, the area of the geometric shape bounded by the dashed lines is simple to calculate, no matter where the hourly time points fall. Let the area of this regular shape be A. L_s and L_j and thus $L_{\max}$ are known, and all the time points on the figure (points t_1 through t_6) are known or are calculated by MACCS. Thus, for any one-hour time period, L_{av}, the average value of L_{sj} during that time period, is given by $L_{av} = A/(t_5 - t_3)$. Since $t_5 - t_3 = 1$ hr, $L_{av} = A$. The hourly average fraction of plume segment length f_{av} that lies over a radial interval during the storm is given by $f_{av} = L_{av}/L_s$. So, f_{av} can be calculated hour-by-hour for each plume segment and every radial interval.

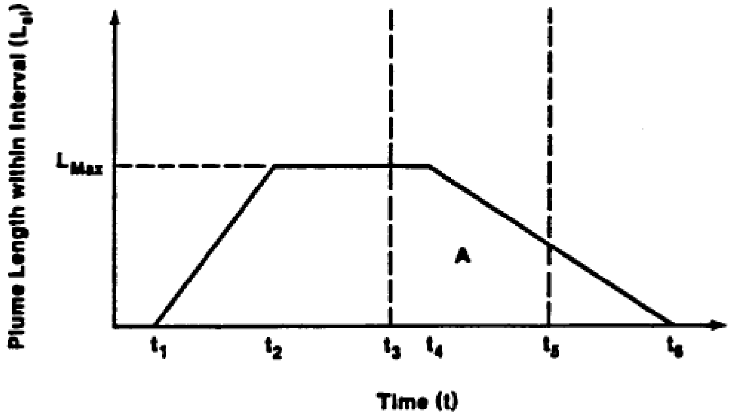

Figure 2-6 Plume Segment Length Over a Radial Interval vs Time

The quantity f_{av} now must be introduced into Equation (2-45). To see how this is done, let Δt_w be the time required for the full plume segment to traverse both the inner and outer edge of a given radial interval.

Note that the plume segment transport time over a given radial interval for dry deposition, Δt_{ref}, the plume segment transport time over a given radial interval for wet deposition, Δt_w, and the plume segment transport time overhead a stationary individual, Δt_e, are all different.

If the transport time Δt_w is several hours long, then $\Delta t_w = \sum_i \Delta t_i$ where the first and last values of Δt_i can be fractional hours. Let $f_{av,i}$ be the average fraction of the plume segment within the radial interval during Δt_i, and let $\overline{f_w}$ be the fraction of aerosol removed by wet deposition within the radial interval. The fraction of aerosol $\overline{f_{wi}}$ removed during Δt_i is then the following.

$$\overline{f_{wi}} = f_{av,i} \cdot \overline{f_w} \tag{2-46}$$

Where $\overline{f_{wi}}$ and $\overline{f_w}$ are the complements of the fraction of material not removed from the plume (i.e., $\overline{f_{wi}} = 1 - f_{wi}$ and $\overline{f_w} = 1 - f_w$). Recall that f_w was previously derived in Equation (2-45). By substituting Equation (2-44) for time step *i* into the formula above and solving for f_{wi} gives the following:

$$f_{wi} = 1 - f_{av,i} \cdot \left(1 - exp\left[-C_1 \left(\frac{I_i}{I_0}\right)^{C_2} \Delta t_i\right]\right) \tag{2-47}$$

And f_w, the fraction of aerosol remaining in the plume after deposition only onto the radial interval during all of the time steps *i* required to transport the plume segment across the radial interval, is given by the product of these fractions:

$$f_w = \prod_i f_{wi} \tag{2-48}$$

2.8 Centerline Air and Ground Concentrations

As modeled in MACCS, dry and wet deposition are independent processes. For example, assume that during transport across a radial interval dry deposition alone would deplete a plume segment of one-tenth of the material in the segment, and wet deposition alone would remove one-half of the material in the segment. Then, if the two processes are independent and occur simultaneously, the fraction of the material in the segment upon entry into the radial interval, that remains when the segment leaves the radial interval, is 0.45 = (1.0 - 0.1)(1.0 - 0.5). Thus, the total amount of material ΔQ_j deposited onto the ground during transport of a plume segment across radial interval j is given by,

$$\Delta Q_j = Q_j\left(1 - f_{dj} \cdot f_{wj}\right) \quad \textbf{(2-49)}$$

Where

- Q_j is the amount of radioactive material (*Bq*) that is transported into interval j by the plume segment, discussed in more detail below,

- f_{dj} is the fraction of material (dimensionless) that would remain in the plume after transport across radial interval j if only dry deposition occurred, given by Equation (2-43), and

- f_{wj} is the fraction of material (dimensionless) that would remain in the plume after transport across radial interval j if only wet deposition occurred, given by Equation (2-48).

Under this construct, it then follows that the amount of radioactive material Q_j transported into radial interval j is the following:

$$Q_j = Q_0 \cdot \prod_{n=1}^{j-1} f_{dn} \cdot f_{wn} \quad \textbf{(2-50)}$$

Where

- Q_0 is the released activity (*Bq*), which is the product of RELFRC and CORINV, modified by CORSCA, and

- f_{dn} and f_{wn} are the same as before, except *n* belongs to the set of radial intervals that the plume segment transverses before reaching radial interval *j*.

The amount of material Q_{j+1} still airborne in the plume segment after transport across the radial interval is the following:

$$Q_{j+1} = Q_j - \Delta Q_j \quad \textbf{(2-51)}$$

Now let $GC(y=0)_j$ be the average ground concentration under the plume centerline along the length (L_j) of radial interval j. Then the total amount of material ΔQ_j deposited onto the ground during transport of a plume segment across radial interval j is the following:

$$\begin{aligned} \Delta Q_j &= GC(y=0)_j \cdot L_j \cdot \int_{-\infty}^{\infty} exp\left\{-\frac{y^2}{2{\sigma_y}^2}\right\} dy \\ &= GC(y=0)_j \cdot L_j \cdot \sqrt{2\pi}\sigma_y \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}\sigma_y} exp\left\{-\frac{y^2}{2{\sigma_y}^2}\right\} dy \\ &= GC(y=0)_j \cdot L_j \cdot \sqrt{2\pi}\sigma_y \end{aligned} \tag{2-52}$$

The equation simplifies since the value of the second integral is one. Solving for the average ground concentration $GC(y=0)_j$ under the plume centerline of radial interval j gives the following:

$$GC(y=0)_j = \frac{\Delta Q_j}{\sqrt{2\pi}\sigma_y \cdot L_j} \tag{2-53}$$

Average values for the plume source activity $\overline{Q}_j$, lateral dispersion $\bar{\sigma}_{y,j}$, vertical dispersion $\bar{\sigma}_{z,j}$, plume height $\overline{h}_j$, and average windspeed $\bar{u}_j$ for transport of a plume segment across radial interval j are given by the following:

$$\begin{aligned} \overline{Q}_j &= Q_j - 0.5 \cdot \Delta Q_j \\ \bar{\sigma}_{y,j} &= 0.5 \cdot (\sigma_{y,j} + \sigma_{y,j+1}) \\ \bar{\sigma}_{z,j} &= 0.5 \cdot (\sigma_{z,j} + \sigma_{z,j+1}) \\ \overline{h}_j &= 0.5 \cdot (h_j + h_{j+1}) \\ \bar{u}_j &= \frac{L_j}{t_{j+1} - t_j} \end{aligned} \tag{2-54}$$

where the subscripts j and j + 1 signify that the value of the parameter pertains respectively to the inner and outer edges of the radial interval (the values when the reference location of the plume segment enters and leaves the radial interval), and L_j is the length of the radial interval.

The centerline dispersion factor $\frac{\chi}{Q}(x = x_j, y = 0, z = h)$ for radial interval j and the ground-level dispersion factor under the plume centerline $\frac{\chi}{Q}(x = x_j, y = 0, z = 0)$ for radial interval j can be derived at the downwind distance x_j.

Recall from Equation (2-19) that the profile of the plume $\chi(x, y, z)$ is expressed as follows:

$$\chi(x,y,z) = \frac{Q}{u} \cdot f_G(y) \cdot \psi(z) \quad \text{for } z \in [0, H] \tag{2-55}$$

Where

- $\psi(z)$ is the vertical distribution (*m*$^{-1}$), which at short distances is a Gaussian distribution with mirrored reflections [Equation (2-20)], and at long distances is a uniform distribution [Equation (2-21)],

- $f_G(y)$ is the lateral Gaussian distribution (*m*$^{-1}$) in the crosswind direction, as shown in Equation (2-18),

- Q is the released activity (*Bq*), and

- u is the windspeed (*m/s*).

The centerline air concentration $\chi\left(z = \bar{h}\right)_j$ for radial interval *j* can be derived by solving for the centerline location $\left(x = x_j, y = 0, z = h\right)$ and using the average values for radial interval *j* as given in the set of Equations (2-54):

$$\chi\left(z = \bar{h}\right)_j = \frac{\overline{Q}_j}{\sqrt{2\pi}\bar{\sigma}_{y,j}\bar{u}_j} \cdot \psi_j\left(\bar{h}\right) \quad \textbf{(2-56)}$$

The centerline dispersion factor $\frac{\chi}{Q}\left(z = \bar{h}\right)_j$ for radial interval *j* can be derived the same way by also dividing Equation (2-55) by the release activity Q:

$$\frac{\chi}{Q}\left(z = \bar{h}\right)_j = \frac{1}{\sqrt{2\pi}\bar{\sigma}_{y,j}\bar{u}_j} \cdot \psi_j\left(\bar{h}\right) \quad \textbf{(2-57)}$$

By repeating the process and instead solving for the ground-level location $\left(x = x_j, y = 0, z = 0\right)$, the same steps give the ground-level air concentration $\chi(z = 0)_j$ for radial interval *j*:

$$\chi(z = 0)_j = \frac{\overline{Q}_j}{\sqrt{2\pi}\bar{\sigma}_{y,j}\bar{u}_j} \cdot \psi_j(0) \quad \textbf{(2-58)}$$

As well as the ground-level dispersion factor $\frac{\chi}{Q}(z = 0)_j$ for radial interval *j*:

$$\frac{\chi}{Q}(z = 0)_j = \frac{1}{\sqrt{2\pi}\bar{\sigma}_{y,j}\bar{u}_j} \cdot \psi_j(0) \quad \textbf{(2-59)}$$

Finally, the ratio R_j of the ground-level to centerline air concentration at radial interval *j* can be found by the following equation:

$$R_j = \frac{\psi_j(0)}{\psi_j\left(\bar{h}\right)} \quad \textbf{(2-60)}$$

2.9 Atmospheric Transport Model Outputs

MACCS calculates atmospheric transport results at the midpoint of each radial interval traversed by the plume segment. MACCS reports two sets of results related to the atmospheric transport: “Type 0” results that provide summary results from a CCDF, and “Debug Output” results that report results from individual weather trials. The two sets contain many of the same parameters.

<u>Type 0 Results: Atmospheric Results at Specified Downwind Distances</u>

The first set is a group of outputs for a single user-specified plume segment (INDREL) and for a single radial interval (INDRAD). The user also selects a radionuclide of interest (NUCOUT), such as iodine-131. Like most outputs, MACCS computes a CCDF when many weather simulations are run, and summary statistics of these results are available in the output file when requested. The outputs and their derivations are described in Table 2-6:

Table 2-6 Complimentary Cumulative Distribution Function of Atmospheric Results

Output Name (for I-131)	Description	Derivation
I-131 Center Air Conc. (*Bq-s/m³*)	Centerline integrated air concentration ($z = H$) from this plume segment averaged over the radial interval's length	Equation (2-56), adjusted by decay and ingrowth
I-131 Ground Air Conc. (*Bq-s/m³*)	Centerline ground-level integrated air concentration ($z = 0$) from this plume segment averaged over the radial interval's length (*Bq-s/m³*)	Equation (2-58), adjusted by decay and ingrowth
I-131 Center Ground Conc. (*Bq/m²*)	Centerline ground concentration after passage of this plume averaged over the radial interval's length (*Bq/m²*)	Equation (2-53), adjusted by decay and ingrowth
Total Center Ground Conc. (*Bq/m²*)	Total Centerline ground concentration after passage of this plume averaged over the radial interval's length (*Bq/m²*)	Equation (2-53), summed over all radionuclides, adjusted by decay and ingrowth
Ground-Level Dilution, χ/Q (*s/m³*)	Centerline ground-level χ/Q; the ratio of air concentration (χ) to source strength (Q) averaged over the interval's length, not accounting for radioactive decay or deposition (*s/m³*)	Equation (2-59)
I-131 Adjusted[a] Source, Q (*Bq*)	Adjusted[a] source strength of the plume upon entering each radial interval after adjustment for losses in the previous intervals due to radioactive decay and wet and dry deposition (*Bq*)	Equation (2-50), adjusted by decay and ingrowth
Plume Sigma-y (*m*)	Lateral dispersion parameter $\bar{\sigma}_y$ averaged over the radial interval's length	Equations (2-54)
Plume Sigma-z (*m*)	Vertical dispersion parameter $\bar{\sigma}_z$ averaged over the radial interval's length	Equations (2-54)
Plume Height (*m*)	Average plume centerline height as it traverses the radial interval	Equations (2-54)
Plume Arrival Time (*s*)	Time after accident initiation at which the reference location of the plume arrived at the center of the radial interval (*s*)	Equation (2-32) plus the period before plume release (PDELAY)

[a] In the Gaussian plume equations, Q_0 is commonly used to represent the amount released activity. When material decays or is deposited onto the ground during transport, the effective source strength for downwind distances is reduced. This is treated in MACCS through the definition of an adjusted source strength, Q, which is reduced by deposition and radioactive decay that occur over plume trajectory up to the current location. Note that all the concentration results shown in this table account for plume depletion; however, the value for χ/Q does not. This quantity simply represents the normalized concentration (*s/m³*) from dispersion at a downwind distance.

Atmospheric Transport Debug Output

Additionally, another set of atmospheric transport model results are available as part of the debugging tools (IDEBUG), and again for a select radionuclide (NUCOUT). Some of these results are identical outputs to those in the previous table but are not available as a CCDF. Instead, MACCS reports values for every weather simulation, plume segment, and distance interval. The type of output results and derivations are shown in Table 2-7.

Table 2-7 Atmospheric Results Available through debug results (IDEBUG = "1" or "2")

Output Name	Description	Derivation
GL AIRCON	Centerline ground-level integrated air concentration ($z = 0$) from this plume segment averaged over the radial interval's length (*Bq-s/m*^{3})	Equation (2-58), adjusted by decay and ingrowth
GRNCON	Centerline ground concentration after passage of this plume averaged over the radial interval's length (*Bq/m*^{2})	Equation (2-53), adjusted by decay and ingrowth
GL χ/Q	Centerline ground-level χ/Q; the ratio of air concentration (χ) to source strength (Q), averaged over the interval's length (*s/m*^{3})	Equation (2-59)
WETREM	Fraction of material remaining in the plume segment after wet deposition over the radial interval's length (dimensionless)	Equation (2-43)
DRYREM	Fraction of material remaining in the plume segment after dry deposition over the radial interval's length (dimensionless)	Equation (2-48)
REMINV	Adjusted source strength of the plume upon entering each radial interval after adjustment for losses in the previous intervals due to radioactive decay and wet and dry deposition (*Bq*)	Equation (2-51), adjusted by decay and ingrowth
PLSIGY	Lateral dispersion parameter $\bar{\sigma}_y$ averaged over the radial interval's length (*m*)	Equations (2-54)
PLSIGZ	Vertical dispersion parameter $\bar{\sigma}_z$ averaged over the radial interval's length (*m*)	Equations (2-54)
WEATHER	Indices to the first and last hours of the weather sequence used for determining atmospheric conditions during transport across each radial interval (*hr*)	Equation (2-33)
HTFCTR	Ratio of the centerline ground-level air concentration ($z = 0$) to the plume centerline air concentration ($z = H$) (dimensionless)	Equation (2-60)
AVGHIT	Average plume centerline height as it traverses the radial interval (*m*)	Equations (2-54)
TIMCEN	Time after accident initiation at which the reference location of the plume arrived at the center of the radial interval (*s*)	Equation (2-32) plus the period before plume release (PDELAY)
TIMOVH	Duration for which the plume was overhead at the midpoint of the radial interval (*s*)	Equation (2-33)
MXMIXH	Mixing height for this plume segment over the radial interval (*m*)	From mixing height model (see Section 2.3.4)

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3 DOSIMETRY

MACCS uses doses for two main purposes, which are (1) to calculate health effects from ionizing radiation (i.e., radiogenic health effects) and (2) to help determine the location of protective actions. To calculate health effects, MACCS computes three types of doses to organs or tissues: acute doses, lifetime doses, and annual doses. MACCS also computes an effective dose to the whole body, which MACCS treats as a subcategory of lifetime and annual doses. Acute, lifetime, and annual doses are discussed more below. MACCS also reports dose results in the output, as they are an important result in their own accord.

MACCS models the following seven exposure pathways:

(1). External exposure to radioactive material in the plume (cloudshine),

(2). External exposure to radioactive material deposited on the ground (groundshine),

(3). Internal exposure from the inhalation of radionuclides directly from the plume (direct inhalation),

(4). Internal exposure from the inhalation of resuspended material (resuspension inhalation),

(5). External exposure to material deposited onto the skin (skin deposition).

(6). Internal exposure from the ingestion of food from farmland (food ingestion), and

(7). Internal exposure from drinking water ingestion.

MACCS does not model incidental soil ingestion, ingestion of food that comes from gardens or foraged in non-farm areas, or ingestion of fish or other aquatic food. MACCS treats the first five exposure pathways listed above as “direct” pathways, meaning that MACCS tallies these doses when summing the dose contributions to the individual residents in a spatial element. The food and water ingestion pathways are “indirect” pathways, meaning that MACCS does not tally these doses when summing the individual dose contributions. Because of additional transport of food and water, ingestion doses do not necessarily occur in the spatial element where deposition occurs, and MACCS does not attempt to model the actual location. Thus, the reported values of individual doses and associated individual cancer risk in MACCS are based on a partial set of dose contributions.

While not considered in the tally of individual doses (*Sv*), MACCS does consider ingestion doses in the tally of the population dose (*person-Sv*). MACCS also calculates groundshine doses to decontamination workers, which like ingestion, is included in collective metrics but not individual metrics. MACCS tallies the population doses from ingestion and decontamination workers in the spatial element where deposition occurs. As such, collective metrics (e.g., population doses, number of health effects) that consider both direct and indirect pathways are more complete measures of accident consequence than individual metrics that only consider direct pathways.

MACCS divides the calculation of radiation doses into two domains: “early” exposure during and shortly after plume passage (i.e., early phase), and “late” exposure after the early phase (i.e., intermediate, and long-term phases). The start of the early phase exposure depends on the protective action model and lasts for a fixed duration of ENDEMP days. Outside the evacuation boundary set by the parameter NUMEVA and inside the evacuation boundary when the user selects an emergency response based on plume arrival (REFPNT = "ARRIVAL"), early phase exposure begins when the first plume segment arrives to the given spatial element. Therefore, the start and end of the early exposure calculation differ by location. Inside the evacuation boundary, when the user chooses to use an alarm time (REFPNT = "ALARM"), the early phase exposure calculation instead begins at the user-specified alarm time (OALARM) and does not differ by location.

For the intermediate and long-term phases, the CHRONC module calculates the ground concentration ENDEMP days after the start of accident. CHRONC treats this time as the start of the calculation, which does not differ by location. Because the end of the early phase exposures can be after this time, there is some overlap in the early and late exposure periods and the amount depends on the selection of parameters. Late exposure periods can depend on the pathway and are discussed in more detail in Section 3.4.

Doses from exposures during the early phase (i.e., early doses) include the following 5 pathways:

(1). Cloudshine,

(2). Groundshine,

(3). Direct inhalation,

(4). Resuspension inhalation, and

(5). Skin deposition.

The early phase dose equations in Section 3.3 are for a single plume segment. To estimate an early dose in a spatial element from all plume segments, MACCS calculates a dose from each plume segment and sums them together. Even though inhalation has a commitment period that extends beyond the length of the early phase, MACCS assigns the dose from internal exposures to the period when the intake occurs. The exception to this is when MACCS is calculating an annual dose, in which case MACCS assigns the dose to the annual period when decay occurs rather than when intake occurs. MACCS assumes ingestion is not relevant in the early phase.

Doses from exposures during the intermediate or long-term phase (i.e., late doses) include the following 4 pathways:

(1). Groundshine,

(2). Resuspension inhalation,

(3). Food ingestion, and

(4). Water ingestion.

The late dose equations in Section 3.4 are for all plume segments. The late doses are based on a ground concentration at the end of the early phase and is a sum of ground concentrations from all plume segments. Since the plume has passed, cloudshine and direct inhalation are not relevant after the early phase. For the food and water ingestion pathways, transport of deposited radionuclides into the food and drinking water supply begins when the early phase ends. MACCS also tallies decontamination worker doses with the other late doses.

Doses that determine when a protective action is taken are based on dose projections to a stationary individual that receives a dose as if no protective actions were to occur. Dose levels for radiation protection are commonly based on the effective dose to the whole body, but depending on what the user specifies, they can also be based on an organ dose.

The dosimetry models in Section 3 depend on the protective actions that impact the duration of exposure, the activities of the cohort, and ground concentrations. Section 4 discusses different protective actions modeled in MACCS during the early phase, the intermediate phase, and the long-term phase. These protective actions reduce the dose that cohorts would otherwise receive, but they also produce other types of consequences as discussed in Section 5.

MACCS uses acute, lifetime, and annual doses to compute radiogenic health effects. MACCS may also use the effective dose when computing health effects (indirectly), as a measure of when to truncate or modify low dose cancer risks when using an annual-threshold or piecewise-linear dose-response option. These topics are discussed more in Section 6.

Types of Calculated Doses

MACCS quantifies three types of doses:

(1). Acute doses (designated by A- in MACCS)

(2). Lifetime doses (designated by L- in MACCS)

(3). Annual doses (designated by L- in MACCS)

MACCS also calculates the effective dose to the whole body, although MACCS treats the effective dose no differently than a lifetime or annual dose to an organ. The acute, lifetime, and annual doses provide dose estimates for assessing health effects of ionizing radiation. The acute, lifetime, and annual doses are doses to organs (or tissues), but they typically consider different exposure periods and may be weighted by different values of RBE.

Acute dose is the portion of the dose that contributes to early health effects. Early health effects can only occur when a high enough dose is delivered over a short enough period, as this is a necessary condition for radiation damage to overwhelm the ability for tissue to repair itself. Therefore, for early health effects, the biological response exhibits a sparing effect where the body can better cope with higher doses when they are delivered over a long period than it otherwise could.

To account for the sparing effect, MACCS only tallies exposures from the early phase in the acute dose calculation, as this is the only period in which doses may be high enough to cause acute health effects. Additionally, inhalation exposures from the early phase can have a long dose commitment period. To account for the fact that only a fraction of a protracted dose may contribute early health effects, acute inhalation doses use a time weighting factor to reflect the reduced impact. This time weighting factor is part of the acute inhalation dose coefficient, which are discussed in the next section.

Despite the potential length of the early phase, MACCS does not explicitly consider the sparing effect in the early external exposures. In most cases, however, the sparing effect from early external exposures is likely small, as emergency plans should ensure that no individuals are permitted to remain in a contaminated area for much longer than one day when dose levels are high enough to pose a risk of early health effects.

The **lifetime dose** is the dose that contributes to stochastic health effects (e.g., cancer). Lifetime doses may include all exposure pathways from the early, intermediate, and long-term phases. Lifetime doses include external doses over a person's remaining lifetime (usually assumed to be 50 years from the time of initial exposure) plus committed doses from internal exposure. Committed doses account for the entire dose from an internal exposure over an assumed 50-year commitment period. Committed doses account for both radioactive and biological half-lives.

The lifetime dose is like a related quantity known as the "equivalent dose," as both are intended to evaluate the risk of stochastic health effects. However, equivalent doses use the ICRP radiation weighting factors. The purpose of an equivalent dose is to provide a simple standard for radiation protection. Lifetime doses use a weighting known as a RBE to evaluate the biological effect of an absorbed dose. Therefore, lifetime doses are more appropriate to use than equivalent doses for quantifying cancer risk.

In practice, RBEs and radiation weighting factors can be the same. However, RBE values can be organ-specific and radiation weighting factors are not. Unless the lifetime dose coefficients use a radiation weighting factor instead of an RBE, MACCS does not calculate equivalent doses. Nevertheless, the lifetime dose is usually a close surrogate to the equivalent dose, and depending on the RBE, they may be numerically the same. If a dose for radiation protection for an organ is needed, the user may choose to use the lifetime dose (e.g., L-THYROID) as a surrogate.

The effective dose is the tissue-weighted sum of the equivalent doses of specific organs and is intended to represent a stochastic health risk to a complete individual. Users commonly use the effective dose as an input to the protective action models to determine when to enact certain protective actions. Outside of MACCS, this dose is commonly estimated by first calculating the doses received by various organs and then applying the radiation- and tissue-weighting factors to derive a whole-body dose. MACCS instead calculates the effective dose to the whole body just as it would treat one more organ (i.e., L-ICRP60ED). The effective dose has its own set of dose coefficients that have already been weighted by the tissue weighting factors. As such, the calculation of the effective dose only depends on the radionuclide and pathway. Because of how MACCS calculates the effective dose, the effective dose is sometimes referred to as a pseudo-organ. When a risk coefficient is available, MACCS can also estimate stochastic health effects using the effective dose. However, this is not the preferred method as it is not as precise as considering lifetime doses to individual organs. Additionally, since MACCS treats the effective dose as just one additional organ, output tallies that sum total cancer effects are susceptible to double counting when assessing cancers from both organ doses and the effective dose, depending on what the effective dose risk coefficient represents.

Annual doses are the same as the lifetime dose, except the annual doses are discretized into annual periods. Annual doses support the use of certain dose-response relationships (i.e., the annual-threshold and piecewise-linear dose-response options) that require MACCS to provide doses in annual periods. Dose-response modeling capabilities are discussed in more detail in Section 6.

MACCS uses essentially the same dose equations for lifetime and annual doses but uses slightly different considerations. For external exposures, MACCS calculates annual doses using the same dose coefficients. The difference is that the code limits the dose integration to the applicable annual periods.

To estimate annual doses from internal pathways, the same dose coefficient as the lifetime dose cannot be used, as internal dose coefficients represent a dose over a commitment period of up to 50 years. Instead, MACCS requires annual dose coefficients that divide the lifetime commitment period into 50 annual periods. The sum of the 50 annual dose coefficients is then equal to the full lifetime dose coefficient.

In this way, MACCS divides the dose from each intake period and assigns them to different years. An intake in the first year leads to annual doses in years 1 to 50; an intake in the second year leads to annual doses in years 2 to 51, and so on. In MACCS, the last year that intake can occur when using COMIDA2 is year 9, and therefore there can be up to 58 annual doses. MACCS assigns the first-year dose of the commitment period to the year that intake occurs, regardless of whether that some of the intake may occur towards the end of the year or not. The first annual period includes doses during the early phase, making the first annual period slightly longer than the others. MACCS then sums the contributions from the different intake periods to find all the annual internal doses, which are then summed with the external annual doses to obtain the annual doses from all pathways.

Dose Equations

Sections 3.3 and 3.4 describe the individual dose equations for each exposure pathway. While the dose equations are different for each exposure pathway, in general, all dose calculations are based on the radionuclide concentration, the dose coefficients, the protection factor, the exposure period, and potentially other pathway-specific factors. For example, the dose equation for the direct inhalation exposure pathway is based on the ground-level air concentration in a spatial element, inhalation dose coefficient, breathing rate, inhalation protection factor, and the duration of exposure.

The radionuclide concentrations are a result of the atmospheric transport calculations. For a given plume segment and radial interval, the atmospheric transport model calculates the following concentration for each radionuclide *i*:

- χ_i^C, the time-integrated air concentration at the plume centerline (*Bq-s/m*^{3}), Equation (2-56)
- χ_i^G, the time-integrated ground-level air concentration (*Bq-s/m*^{3}), Equation (2-58)
- GC_i, the ground concentration under the plume centerline (*Bq/m*^{2}), Equation (2-53)

Note that each of these values are concentrations either under or at the plume centerline. As discussed in Section 3.2, the dose equations use off-centerline correction factors to account for areas not directly under or at the plume centerline.

Early dose equations use one of three concentrations above. For each plume segment, the concentrations are adjusted for decay and ingrowth for the period between the start of the accident until the plume segment leaves the spatial element. For each early exposure pathway, there is a dose calculation for each plume segment, potentially more to account for evacuees moving through spatial elements.

Late dose equations are based on the sum of undecayed ground concentrations from all plume segments, and then adjusted for decay and ingrowth from the start of the accident until the end of the early phase (ENDEMP). After this point in time, the exposure pathways account for decay and ingrowth as part of the dose equations.

The dose coefficients, sometimes called dose conversion factors (DCFs), are calculation inputs that MACCS uses to convert the radionuclide concentrations into either doses or dose rates for each radionuclide, pathway, and organ. The user provides most of these in the DCF file(s) discussed next in Section 3.1. MACCS calculates the skin deposition dose coefficient internally (Section 3.3.5). If the user chooses to the COMIDA2 food-chain pathway, COMIDA2 provides the food ingestion dose coefficients (Section 3.4.3.1).

The protection factor is a dimensionless quantity that reduces the radiation dose according to the anticipated protection from a given exposure pathway. The user specifies the protection factors for different exposure pathways. In the early phase, protection factors can also be different for people in different states of activity (i.e., evacuation, normal, sheltering), as discussed in Section 4.

The exposure period depends on the exposure pathway and the period that an individual resides in the spatial element. As discussed in Section 4, the protective actions within a spatial element can significantly limit the exposure duration. If the plume never entered a spatial element, the radiation dose individuals receive in that spatial element is zero.

3.1 Dose Conversion

The dose modeling approach in MACCS requires dose coefficients, also known as dose conversion factors (DCFs), to convert from a concentration to a dose. MACCS uses dose coefficients to (1) quantify acute doses for estimating early health effects, (2) the lifetime dose for estimating cancer effects, and (3) annual doses, also for estimating cancer effects.

MACCS requires an external file to supply the dose coefficients. Since it was originally released, MACCS has been distributed with several DCF files. More information on the available dose coefficients is discussed in the MACCS User's Guide (SAND-2021-1588).

MACCS has a fixed set of organs for which the code can calculate doses. The set of organs depends on which type of dose conversion factor file is used. The names of the organ doses in MACCS are based on the type of organ and have a prefix of "A-" for acute doses and "L-" for lifetime doses. (For instance, the dose name for the acute dose coefficient for STOMACH is "A-STOMACH.") For the user to select an organ dose for MACCS to calculate, the parameter ORGFLG for the organ must be set to "TRUE," and there must be a matching organ name in the DCF file.

Calculating the acute and lifetime doses require dose coefficients for each organ, each radionuclide, and each applicable pathway. Acute and lifetime doses may also require different dose coefficients because deterministic and stochastic effects can have different RBEs, and also because the acute inhalation doses from the early phase require a time weighting to account for the sparing effect.

Since MACCS considers a total of seven dose exposure pathways (i.e., cloudshine, groundshine, direct inhalation, resuspended inhalation, skin deposition, food ingestion, and water ingestion) and calculates separate doses for early health effects and stochastic health effects, it may seem that MACCS should require up to fourteen sets of dose coefficients. However, many of these are not required or contain redundant information for the following reasons:

- Direct inhalation and resuspended inhalation are effectively the same pathway and have the same set of dose coefficients DCI_{ik}. These exposures only differ in the origin of the contamination.
- Similarly, food and water ingestion are effectively the same pathway and have the same set of dose coefficients DCW_{ik},
- The dose rate coefficient for skin deposition $DRCS_i$ is a fixed value in the code.
- MACCS does not require acute dose coefficients for ingestion. MACCS assumes that only exposures in the early phase are capable of inducing early health effects, and that no ingestion of contaminated food or water occurs in the early phase.
- MACCS assumes that the cloudshine and groundshine dose coefficients can be used for both acute and lifetime doses, for two reasons:
    - MACCS assumes that these pathways either fully contribute to acute doses (i.e., during the early phase) or not at all (i.e., after the early phase). The acute dose calculation for these pathways do not require a special time-weighting to account for the sparing effect.
    - Since external doses are exposures with low linear energy transfers (i.e., gamma rays), MACCS assumes that deterministic and stochastic effects use the same RBE value.

As such, MACCS requires dose coefficients to organ k for radionuclide i for just five exposure types:

- $DRCC_{\infty ik}$ is the semi-infinite cloudshine dose rate coefficient (*Sv-m*^{3}*/Bq-s*), used for estimating both early health effects and cancer risk,
- $DRCG_{ik}$ is the groundshine dose rate coefficient (*Sv-m*^{2}*/Bq-s*), used for estimating both early health effects and cancer risk,
- DCI_{ik}^{A} is the acute inhalation dose coefficient (*Sv/Bq-inhaled*), used for estimating early health effects,

- DCI_{ik}^{L} is the lifetime inhalation dose coefficient (*Sv/Bq-inhaled*), used for estimating cancer risk, and

- DCW_{ik} is the lifetime ingestion dose coefficient (*Sv/Bq-ingested*), used for estimating cancer risk.

The internal pathway dose coefficients (i.e., inhalation, ingestion) are typically based on a commitment period of 50 years. The original version of MACCS also required dose coefficients for an 8-hour and 7-day cumulative groundshine dose. Even though they are no longer used, these fields may still exist in newer DCF files to remain backward compatible.

For all the early phase pathways (except skin deposition[9]), MACCS calculates both acute and lifetime doses. MACCS assumes that external exposures fully contribute to the acute doses in the early phase, meaning that the sparing effect does not reduce early health effects. Therefore, dose calculations for cloudshine and groundshine use the same set of dose coefficients for acute and lifetime doses. On the other hand, MACCS does require a separate set of acute dose coefficients for the inhalation pathway, and this set of acute dose coefficients should account for the sparing effect. The set of acute inhalation dose coefficients is typically for a smaller set of organs that may be susceptible to early health effects.

Doses over a protracted commitment period are less effective at causing early health effects than an immediate dose. To account for the sparing effect, the acute inhalation dose coefficients should contain a time weighting factor. To determine the appropriate time weighting factor, the developer of the dose coefficients first divides the dose commitment period into smaller periods. A weighting factor reflecting the contribution to the acute dose is then applied to each period. The weighting factors are greater early in the commitment period and become progressively smaller, until no more contributions to the acute dose is warranted. The weighted sum of the dose in these periods then gives the estimated acute dose from the full protracted dose commitment period.

If the user chooses to use the annual-threshold or piecewise-linear dose-response option, the lifetime dose from the internal pathways (i.e., chronic inhalation and ingestion) must be divided into periods that reflect the year that the dose contribution occurs so that MACCS can calculate annual doses. As such, MACCS requires dose coefficients for each year of the 50-year commitment period. This requires the user to provide an additional 50 DCF files, one for each year, containing the dose coefficients for inhalation and ingestion pathways. These dose-response options are discussed in more detail in Section 6. This is only for the internal pathways, as the external pathways have no commitment period. With this, MACCS can calculate the lifetime dose contributions for each year of the analysis.

3.2 Off-Centerline Correction Factors

In order to calculate the radiation doses at off-centerline locations, the dose equations modify the centerline radionuclide concentrations by the appropriate off-centerline correction factors. As

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[9] MACCS does not calculate a lifetime dose from skin deposition.

discussed in Section 1.2, the location of a spatial element is specified by its radial interval (r) and compass sector (s).

Section 1.2 describes the basic nodalization of the spatial grid. In addition to the regular spatial elements in the basic grid, MACCS uses a more refined set of spatial elements, called fine spatial elements, to calculate off-centerline doses during the early phase. The fine spatial elements are the same as the coarse spatial elements but are divided into more compass directions. The user can assign either 3, 5, or 7 fine grid divisions within every spatial element with the parameter NUMFIN.

The dose equations use four different off-centerline correction factors; three of them are used for the early phase.

- The standard correction factor J_{rm} for fine spatial elements used for most of the dose pathways in EARLY.
- The top-hat correction factor U_{rs} used for most of the dose exposure pathways during evacuation in EARLY.
- The cloudshine correction factor C_{rm} for fine spatial elements used in EARLY.
- The standard correction factor K_{rs} for coarse spatial elements used for all exposure pathways in CHRONC.

Here, *r* is the radial interval number, *m* is the number of fine spatial elements from the plume centerline, and *s* is the number of coarse spatial elements from the plume centerline. The first spatial element (i.e., $m=1$ or $s=1$) is directly centered along the plume centerline.

For stationary individuals in the early phase, the dose equations use off-centerline correction factors for fine spatial elements. Early phase dose equations based on ground concentrations or ground-level air concentrations (i.e., groundshine, direct inhalation, resuspension inhalation, and skin deposition) use the standard off-centerline correction factor J_{rm}.

J_{rm} is appropriate for stationary people. During evacuation, MACCS instead uses a top-hat approximation as a simplification.

Cloudshine uses a special off-centerline correction factor C_{rm} that accounts for the size of the plume and the distance from the receptor to the plume centerline. After the plume is fully vertically dispersed, the cloudshine dose calculation uses the standard off-centerline correction factor J_{rm} like the other dose equations.

Late dose calculations do not use the fine spatial elements, but instead use a different off-centerline correction factor K_{rs} calculated from J_{rm}.

In order to simplify the notation, the early dose equations in Section 3.3 do not use subscripts *r* and *m*. Therefore, the off-centerline correction factors of a fine spatial element are C for the cloudshine and *J* for the other early exposure pathways instead of C_{rm} and J_{rm}.

The Standard Correction Factor for Fine Spatial Elements

For stationary people, MACCS uses a multistep histogram to approximate the Gaussian plume lateral distribution for calculating the off-centerline correction factor J_{rm}, where the fine spatial elements specify the steps of the histogram. Even though the width of Gaussian distribution is infinite, MACCS only includes the fine spatial elements that are within a cutoff height of one-tenth of the centerline concentration and assumes areas outside of this are negligible. Therefore, the outermost fine spatial elements that are included in the calculation contain the points at which the lateral distance is $\pm 2.15\sigma_y$ from the plume centerline.

Figure 3-1 shows an example of a histogram approximation to the lateral Gaussian distribution in the crosswind direction. The example in this figure has the following characteristics:

- the number of compass sectors (NUMCOR) is 16,
- the number of fine grid divisions per compass sector (NUMFIN) is 3,
- the angle of each compass sector is $2\pi/16$,
- the angle of each fine division $\Delta\theta$ is $2\pi/(16 \cdot 3)$,
- the outermost histogram step *M* is 4, and
- the total number of fine spatial elements that contribute is 7.

The outermost histogram step *M* is derived later in this section.

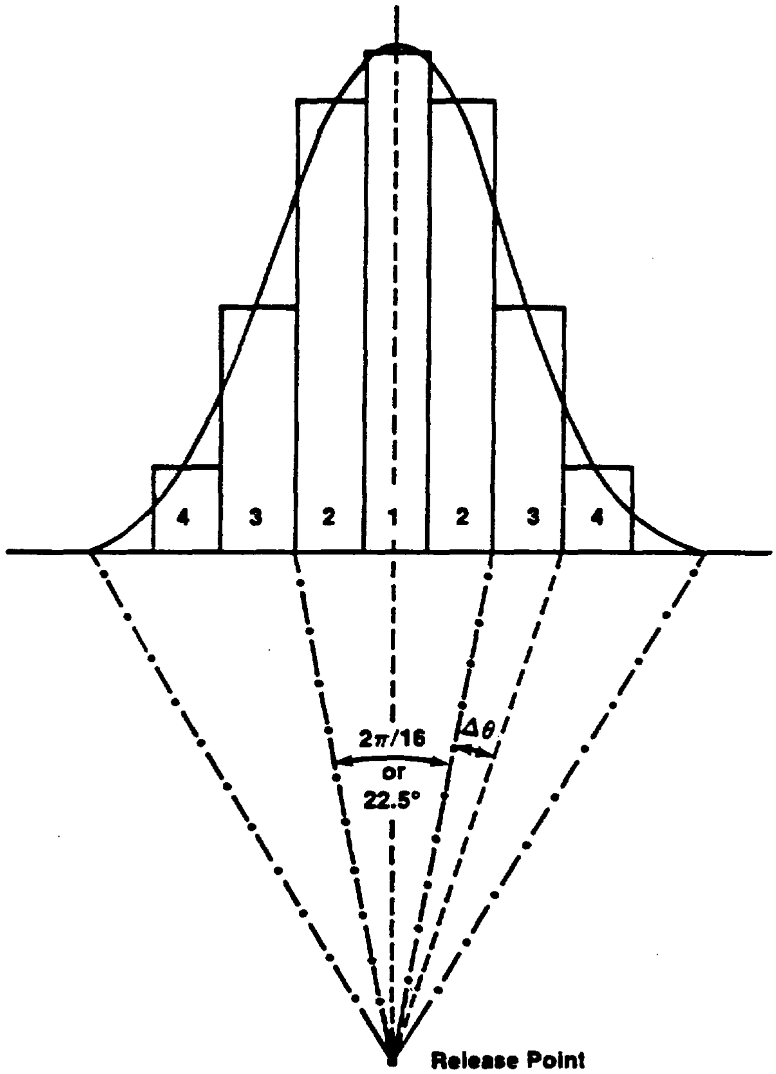

Figure 3-1 Approximation of a Gaussian Distribution by Fine Spatial Elements

The off-centerline correction factor J_{rm} is the ratio of the density of the histogram H_{rm} for fine spatial element (*r*, *m*) to the density of the Gaussian peak. J_{rm} may be calculated using the following equation:

$$J_{rm} = \frac{H_{rm}}{f_G(y = 0)} = \sqrt{2\pi}\sigma_y \cdot H_{rm} \qquad \textbf{(3-1)}$$

Where

- J_{rm} is the off-centerline correction factor (dimensionless) for stationary people in a fine spatial element (*r.m*), where *r* is the radial interval number and *m* is the number of steps from the plume centerline,
- H_{rm} is the density of the histogram (m^{-1}) in spatial element (*r*, *m*),

- $f_G(y = 0)$ is the Gaussian distribution (m^{-1}) at the plume centerline at the midpoint of the radial interval, and

- σ_y is the standard deviation (*m*) of the lateral Gaussian distribution at the midpoint of the radial interval.

The density of the histogram H_{rm} is the average density of the Gaussian distribution between the inner and outer edges of the fine spatial element (*r.m*) in the lateral direction, as shown in the following expression:

$$H_{rm} = \frac{\int_{y_{r,m}}^{y_{r,m+1}} f_G(y)dy}{y_{r,m+1} - y_{r,m}} \quad \textbf{(3-2)}$$

Where

- $f_G(y)$ is the Gaussian distribution (m^{-1}) at the midpoint of the radial interval,

- $y_{r,m}$ and $y_{r,m+1}$ are the lateral distances (*m*) from the plume centerline to the inner and outer edges of the fine spatial element *(r,m)*, respectively, at the midpoint of radial interval.

The lateral distance $y_{r,m}$ from the plume centerline to the inner edge of the spatial element *(r,m)* is approximated using the following equation:

$$y_{r,m} \approx R_r \cdot tan\, \theta_m \quad \textbf{(3-3)}$$

Where

- R_r is the radial distance (*m*) from the release point to the midpoint of the radial interval *r*, and

- θ_m is the angle between the plume centerline and the outer edge of histogram step *m*, (i.e., $\theta_m = \left(m - \frac{1}{2}\right) \cdot \Delta\theta$), and

- $\Delta\theta$ is the angle of a fine spatial element, which is the angle of a compass sector (360° / NUMCOR), divided by the number of fine grid divisions within compass sector (NUMFIN).

Note that for the spatial element directly under the plume centerline ($m = 1$), there is no inner edge. For this case, MACCS assumes $y_{r,m=1} = 0$.

To conveniently integrate the Gaussian distribution, the lateral direction y is scaled by the lateral dispersion parameter σ_y (i.e., $y = \sigma_y \cdot t$) to transform the Gaussian equation into a standard normal distribution.

$$\int_{y_{r,m}}^{y_{r,m+1}} f_G(y)dy = \int_{t_{r,m}}^{t_{r,m+1}} \varphi(t)dt = \Phi(t_{r,m+1}) - \Phi(t_{r,m}) \qquad \textbf{(3-4)}$$

Where

- $\varphi(t)$ is the probability density function of the standard normal distribution (i.e., $\sigma_t = 1$),
- $\Phi(t)$ is the cumulative density function of the standard normal distribution,
- $t_{r,m}$ and $t_{r,m+1}$ are the number of standard deviations, σ_y, (dimensionless) from the plume centerline to the inner and outer edges of the fine spatial element *(r,m)*, respectively, at the midpoint of radial interval *r*.

Values for the standard normal distribution function $\Phi(t)$ are stored in a lookup table in MACCS, with values of *t* in steps of 0.01 between [0.00, 3.00]. Results for $\Phi(t)$ are calculated using linear interpolation from the values in the lookup table.

Values for t are derived using $t = y/\sigma_y$ and Equation (3-3). Substituting Equation (3-4) into Equation (3-2), and then into Equation (3-1) gives the following formula for the off-centerline correction factor J_{rm}:

$$J_{rm} = \sqrt{2\pi} \cdot \frac{\Phi(t_{r,m+1}) - \Phi(t_{r,m})}{t_{r,m+1} - t_{r,m}} \qquad \textbf{(3-5)}$$

Where all terms are previously defined.

The outermost histogram step *M* is defined as the step that includes the point that is $2.15\sigma_y$ away from the plume centerline. MACCS determines step *M* by evaluating the outer edges of the histogram steps. The outer edge of step *M* is the first edge where $\tan\theta_M \geq \frac{2.15\sigma_y}{R_r}$, where σ_y and R_r have been previously defined. Then *M* is equal to $\theta_M/\Delta\theta + 0.5$.

<u>Top-Hat Correction Factor During Evacuation</u>

For the purposes of accounting for dose and health effects during an evacuation, the dose received by an evacuee traveling along their evacuation path is attributed to the location in which the evacuee originates. Evacuees travel from one grid element to another in discrete steps. Dose calculations assume evacuees are located at the center of one grid element for a period then suddenly moves to the center of the next grid element along the path of evacuation. The distinction between fine and coarse spatial elements is therefore irrelevant, as evacuees are only located at the midpoint of coarse spatial elements.

During evacuation, MACCS uses the off-centerline correction factor U_{rs} that has the appearance of a top-hat to approximate the lateral Gaussian distribution (Ritchie, et al., 1984). As shown in

Figure 3-2, the correction factor U_{rs} is a uniform distribution with a lateral range of $3\sigma_y$. Within $[-1.5\sigma_y, 1.5\sigma_y]$, the off-centerline correction factor U_{rs} is the ratio of uniform distribution to the gaussian distribution at the plume centerline:

$$U_{rs} = \frac{f_U(y=0)}{f_G(y=0)} = \frac{1/3\sigma_y}{1/\sqrt{2\pi}\sigma_y} = \frac{\sqrt{2\pi}}{3} = 0.836 \qquad \textbf{(3-6)}$$

Where

- $f_U(y)$ is the uniform distribution (m^{-1}) representing lateral dispersion.
- $f_G(y)$ is the Gaussian distribution (m^{-1}) representing lateral dispersion.
- σ_y is the standard deviation (m) of the Gaussian lateral distribution

Because of the nature of a uniform distribution, and because evacuees only exist at the midpoint of a spatial element, evacuees only exist inside the plume ($U_{rs} = 0.836$) or outside the plume ($U_{rs} = 0$).

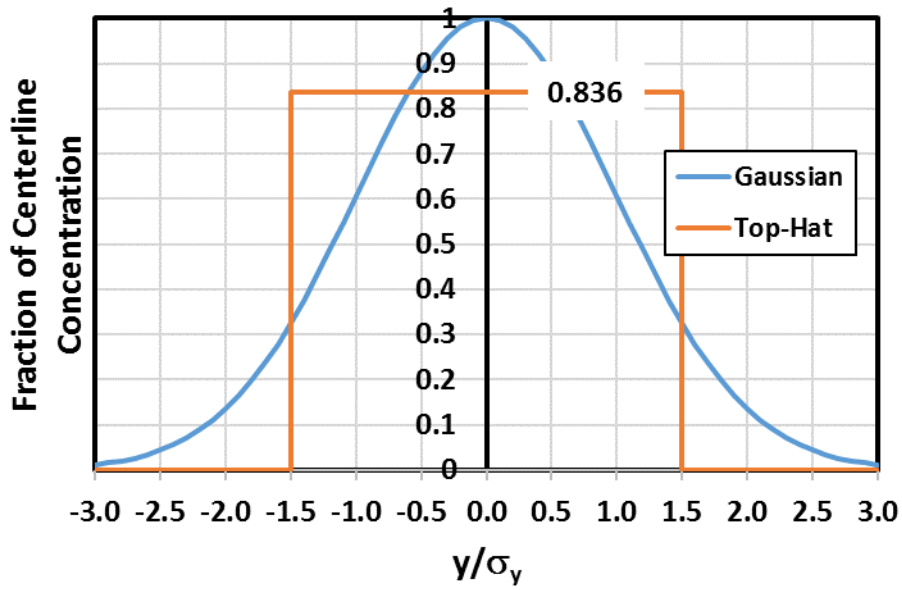

Figure 3-2 Top-hat Approximation of Plume Concentration Used for Evacuee Dosimetry

<u>Cloudshine Correction Factor for Fine Spatial Elements</u>

The cloudshine pathway has its own off-centerline correction factor C_{rm} of a fine spatial element (r,m) that corrects for both the shape of and distance from the plume centerline, which is used for both stationary and evacuating individuals. After the plume is fully vertically dispersed, the cloudshine dose calculation uses the standard correction factor J_{rm}.

The dose coefficients typically provided in the DCF file are for immersion doses in which the cloud is assumed to be uniformly distributed above the ground (i.e., a semi-infinite cloud). The off-centerline correction factor C_{rm} adjusts these dose coefficients so that they reflect a gaussian plume shape. This correction factor is originally based upon formulations by Healy (1984), and dependent on the effective size of the plume and the distance from the plume centerline to the receptor. C_{rm} is based on the geometrical view factor between the plume and the receptor, and it considers both the total distance from the receptor to the plume centerline and the size of the plume. These finite cloud correction factors are fixed values in MACCS and are shown in Table 3-1.

Table 3-1 Finite Cloud Dose Correction Factors[a]

Effective Plume Size, $\sqrt{\sigma_y \sigma_z}$	**Distance to Cloud Centerline Relative to the Effective Plume Size, $\frac{\sqrt{y^2+z^2}}{\sqrt{\sigma_y \sigma_z}}$**					
meters	**0**	**1**	**2**	**3**	**4**	**5**
3	0.020	0.018	0.011	0.007	0.005	0.004
10	0.074	0.060	0.036	0.020	0.015	0.011
20	0.150	0.120	0.065	0.035	0.024	0.016
30	0.220	0.170	0.088	0.046	0.029	0.017
50	0.350	0.250	0.130	0.054	0.028	0.013
100	0.560	0.380	0.150	0.045	0.016	0.004
200	0.760	0.511	0.150	0.024	0.004	0.001
400	0.899	0.600	0.140	0.014	0.001	0.001
1000	0.951	0.600	0.130	0.011	0.001	0.001

[a] Data from Reactor Safety Study Table VI 8-1 with correction of a typographic error of data. For 0.7 MeV gamma photons.

Whereas the Reactor Safety Study (U.S. Nuclear Regulatory Commission, 1975) and CRAC2 use σ_z as the size of the plume, MACCS calculates the effective size of the plume to be $\sqrt{\sigma_y \sigma_z}$ for the purpose of calculating the cloudshine correction factor. MACCS linearly interpolates values from Table 3-1 to obtain off-centerline correction factor C_{rm}.

Standard Correction Factor for Coarse Spatial Elements

The average ground concentration GC_{irs} of radionuclide *i* within a spatial element (*r*,*s*) is the ground concentration under the plume centerline at a distance specified by the radial interval number *r*, multiplied by the off-centerline correction factor K_{rs} for that spatial element.

The coarse off-centerline correction factor K_{rs} is the average of the fine off-centerline correction factors J_{rm} within the coarse spatial element (*r*,*s*), where *r* is the radial interval, *s* is the compass sector, and *m* is the number of fine spatial elements from the plume centerline. More specifically, the value of K_{rs} is the sum of J_{rm} values within a coarse spatial element divided by the number of fine lateral divisions (NUMFIN), which is either 3, 5, or 7.

If there is more than one plume segment passing over a spatial element, the total ground concentration for radionuclide i in a spatial element (r,s) is the sum of ground concentrations of all plume segments:

$$GC_{irs} = \sum_{n=1}^{N} GC_{in} \cdot K_{rsn} \tag{3-7}$$

Where

- GC_{irs} is the ground concentration (*Bq/m²*) of radionuclide *i* at the end of the early phase in spatial element (r,s) as a result of dry and wet deposition from all plume segments,

- GC_{in} is the ground concentration (*Bq/m²*) of radionuclide i at the end of the early phase under the plume centerline as a result of dry and wet deposition from plume segment *n*, as given by Equation (2-53) and adjusted for decay and ingrowth,

- *N* is the total number of plume segments, and

- K_{rsn} is the off-centerline correction factor of the spatial element (r,s) for plume segment *n,* defined above.

To simplify the subscript notation, the spatial element subscripts *r* and *s* are not used in the dose equations of the intermediate and long-term phases. The initial ground concentration of a spatial element (r,s), GC_{irs}, or GC_i, is used for the exposure pathways of the intermediate and long-term phases discussed in the following sections.

3.3 Early Doses

MACCS calculates early doses from the early phase, as requested by the user, when the user gives a value of "FALSE" to the MACCS parameter ENDAT1, which is a parameter that would skip the EARLY module if set to "TRUE."

The calculation of radiation doses from early exposure considers five pathways: (1) cloudshine, (2) groundshine, (3) direct inhalation, (4) resuspension inhalation, and (5) skin deposition. During plume passage, MACCS calculates doses from cloudshine, groundshine, direct inhalation, and skin deposition according to the formulae in dose Equations (3-9), (3-10), (3-12), and (3-15), respectively. After plume passage, MACCS calculates doses from groundshine and resuspension inhalation, as described by (3-10) and (3-13), respectively. Groundshine is the only exposure pathway that MACCS considers both during and after plume passage. MACCS assumes exposure from resuspension inhalation during plume passage is negligible. Likewise, MACCS assumes that exposures from cloudshine, direct inhalation, and skin deposition from residual air concentrations after the plume has passed is also negligible.

Each equation is for a single plume segment. MACCS sums the dose from all plume segments to obtain a dose in a spatial element. Even though inhalation has a commitment period that extends beyond the length of the early phase, MACCS assigns acute and lifetime doses from internal exposures to the period when the intake occurs.

In the early phase, MACCS uses the same dose equations to calculate acute doses, lifetime doses, and annual doses. The only difference among the three doses is the dose coefficient that MACCS uses for internal pathways. For external pathways, the acute, lifetime, and annual dose coefficients are the same. MACCS only uses the acute doses from the early phase to calculate early health effects, while the lifetime and annual doses from all accident phases can contribute to cancer risk.

Dose equations for groundshine and resuspension inhalation are based on the ground concentration at the point in time the plume segment leaves the spatial element. These equations are integrals that depend on the time t_1 that a person enters (or begins in) a given spatial element and the time t_2 that the person leaves that spatial element. Dose equations for cloudshine, direct inhalation, and skin deposition are based on time-integrated air concentrations and the fraction of time F that an individual resides in a spatial element during plume passage. Therefore, the exposure period is limited to the time that a plume enters a given spatial element, t_e, and the time that a plume leaves that spatial element t_o.

During the early phase, the dose to organ k of an individual in a given fine spatial element is the following:

$$D_k = DC_k + DG_k + DI_k + DR_k \tag{3-8}$$

Where

- D_k is the dose (Sv) during the early phase to organ k,
- DC_k is the dose (Sv) from cloudshine,
- DG_k is the dose (Sv) from groundshine,
- DI_k is the dose (Sv) from direct inhalation, and
- DR_k is the dose (Sv) from resuspension inhalation.

When k is an organ, D_k is either the acute dose (used to estimate early health effects) or lifetime dose (used to estimate cancer risk), depending on which type of dose coefficient is used. When k is the whole body, D_k is the effective dose.

In equation (3-8), MACCS assumes that skin deposition DS delivers a negligible dose to most organs. Therefore, skin deposition is not included when estimated organ doses. The only exception to this is when D_k represents the acute skin dose, in which case $D_{skin} = DS_{skin}$. In this special case, MACCS assumes that only the skin deposition pathway contributes to the acute skin dose and that the other pathways are negligible in comparison. As such, skin deposition in MACCS does not contribute to either the lifetime skin dose or a whole-body dose as other exposure pathways do.

During the early phase, to arrive at the total dose to organ k of an individual located in a fine spatial element, the dose must also be summed over all radionuclides, plume segments, and locations where the person receives exposure (only evacuees receive a dose at more than one location).

3.3.1 Cloudshine

Estimates of doses from external exposure to the radioactive plume incorporate a "semi-infinite cloud" approximation (Healy, 1984). For a given plume segment, the cloudshine dose is calculated for each of the fine spatial elements using the following equation:

$$DC_k = \left(\sum_i DRCC_{\infty ik} \cdot \chi_i^C\right) \cdot Y \cdot F \cdot SFC \qquad \textbf{(3-9)}$$

Where

- DC_k is the cloudshine dose (*Sv*) to organ k from the passage of a plume segment over a fine spatial element,
- $DRCC_{\infty ik}$ is the semi-infinite cloud dose rate coefficient ($Sv\text{-}m^3/Bq\text{-}s$) to organ k for radionuclide i, supplied in the DCF file,
- χ_i^C is the time-integrated air concentration ($Bq\text{-}s/m^3$) of radionuclide i at the plume centerline, as calculated by the atmospheric transport model in Equation (2-56) and adjusted for decay and ingrowth,
- Y is the off-centerline correction factor (dimensionless) for a fine spatial element discussed below,
- F is the fraction (dimensionless) of exposure duration during the plume passage, equal to *TE/TO*; where *TE* is the exposure time (*s*) of an individual in the fine spatial element and *TO* is the time duration (*s*) of a plume segment traversing the fine spatial element as given in Equation (2-33), and
- *SFC* is the cloudshine protection factor (dimensionless) due to shielding, as specified by the parameter CSFACT.

The off-centerline correction factor *Y* depends on the vertical distribution of the plume segment. When the vertical profile is a reflective Gaussian distribution, *Y* is the cloudshine correction factor, *C*, which depends on the geometric view factor of the plume segment from the receptor (see Table 3-1). When the plume becomes fully dispersed vertically (i.e., uniform), *Y* is the standard off-centerline correction factor *J* (see Section 3.2).

The time-integrated air concentration at the plume centerline, AC_i^C, represents the whole plume passage duration. However, depending on protective actions, an individual may not be exposed to the full extent of the plume. Therefore, the cloudshine dose DC_k is adjusted by the fraction of exposure duration *F*.

3.3.2 Groundshine

The early phase groundshine dose DG_k depends on a changing dose rate. For a given plume segment, the groundshine dose DG_k (*Sv*) to organ *k* in a fine spatial element is calculated using the following equation:

$$DG_k = \left(\sum_i DRCG_{ik} \cdot GC_i \cdot IEF_i\right) \cdot Y \cdot SFG \tag{3-10}$$

Where

- $DRCG_{ik}$ is the groundshine dose rate coefficient (*Sv-m²/Bq-s*) to organ *k* for radionuclide *i*, supplied in the DCF file,
- GC_i is the ground concentration (*Bq/m²*) of radionuclide *i* under the plume centerline at time t_o when the plume leaves the fine spatial element, as calculated in Equation (2-58) and adjusted for decay and ingrowth,
- IEF_i is the groundshine integrated exposure factor (*s*) for radionuclide *i* discussed below,
- Y is the off-centerline correction factor (dimensionless) discussed below,
- SFG is the groundshine protection factor (dimensionless) due to shielding, specified by the parameter GSHFAC.

The off-centerline correction factor, Y, depends on whether the person is stationary or evacuating. When stationary, Y is the standard off-centerline correction factor, *J*, which depends on the amount of lateral dispersion and the lateral distance from the fine spatial element to the plume centerline. When evacuating, Y is the top-hat correction factor, *U*. Evacuees are either inside the plume ($U = 0.836$) or outside the plume ($U = 0$). See Section 3.2 for more information.

The peak groundshine dose rate GDR_{ik} is equal to the first two terms in the Equation (3-10) (i.e., $GDR_{ik} = DRCG_{ik} \cdot GC_i$.) Because the ground concentration of radionuclide *i* changes with time, individuals are not constantly exposed to the peak groundshine dose rate. To compensate for using the peak groundshine dose rate, MACCS calculates an effective exposure duration that is less than the actual exposure duration, called the integrated exposure factor IEF_i (s).

The integrated exposure factor IEF_i considers the dose rate profile during and after plume passage. Figure 3-3 illustrates the groundshine dose rate as a function of time and the relationships among different event times. In the figure, t_e and t_o are the times that the reference location of the plume segment enters, and leaves a given spatial element, respectively. t_1 and t_2 are the start and end of exposure during the plume passage. t_3 and t_4 are the start and end of exposure after plume passage. These values depend on when people occupy the spatial element, which are determined by the emergency response model in Section 4. An individual can be exposed during plume passage, after plume passage, or both. For an individual exposed both during and after plume passage, both t_2 and t_3 must equal t_o, as there would not be any exposure gap. Once MACCS determines the exposure periods compared to t_e and t_o, the groundshine dose rate profile provides a way to calculate the integrated exposure factor IEF_i. If $t_2 < t_e$, that is, a person leaves a spatial element before the plume enters it, the groundshine dose to that person is zero.

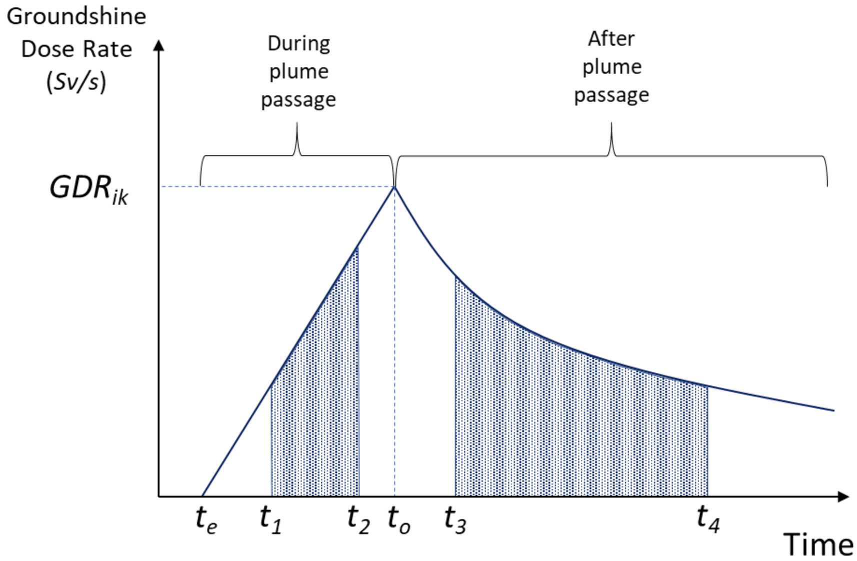

Figure 3-3 Illustration of Groundshine Dose Rate Function and Different Event Times

The groundshine integrated exposure factor IEF_i (s) for the early phase adds the exposure contributions during plume passage and after plume passage. During plume passage, MACCS expresses the groundshine dose rate as a linear increase, which assumes a linear increase in ground deposition. This is an improvement over CRAC2 (Ritchie, et al., 1984), which simply assumed the ground concentration during plume passage to be one-half of its final value. However, MACCS still only accounts for radioactive decay and ingrowth in the groundshine dose rate after plume passage. EED_i is given by the following equation:

$$IEF_i = \int_{t_1}^{t_2} \frac{(t - t_e)}{(t_o - t_e)} dt + \int_{t_3}^{t_4} e^{-\lambda_i t} dt \tag{3-11}$$

Where

- t_e and t_o give the times that the reference location of a plume segment enters and leaves a spatial element,
- t_1 and t_2 give the start and end of exposure during plume passage,
- t_3 and t_4 give the start and end of exposure after plume passage, and
- λ_i is the radioactive decay constant of radionuclide i.

For simplicity, the second integral in Equation (3-11) shows simple decay without ingrowth, even though MACCS considers both decay and ingrowth after plume passage.

3.3.3 Direct Inhalation

MACCS calculates two separate direct inhalation doses, an acute dose for calculating early health effects and a lifetime dose for calculating cancer risk. The two calculations use the same dose equation with different dose coefficients, where the acute dose coefficients have a time weighting to account for the fact that doses delivered over a long commitment period are less effective at inducing acute health effects.

For a given plume segment, the direct inhalation dose during the plume passage is calculated for each of the fine spatial elements using the following equation:

$$DI_k = \left(\sum_i DCI_{ik} \cdot \chi_i^G\right) \cdot BR \cdot Y \cdot F \cdot SFI \tag{3-12}$$

Where

- DI_k is the direct inhalation dose (*Sv*) to organ *k* during passage of a plume segment to an individual in a fine spatial element,

- DCI_{ik} is the inhalation dose coefficient (*Sv/Bq-inhaled*) for either acute or lifetime dose to organ *k* for radionuclide *i*, supplied in the DCF file,

- χ_i^G is the time-integrated ground-level air concentration (*Bq-s/m*^{3}) of radionuclide *i* under the plume centerline, as calculated by the atmospheric transport model in Equation (2-58),

- *BR* is the breathing rate (m^3/s), as specified by the parameter BRRATE,

- *Y* is the off-centerline correction factor (dimensionless) discussed below,

- *F* is the fraction of exposure duration during the plume passage, equal to *TE/TO*; where *TE* is the exposure time (s) of an individual in the fine spatial element and *TO* is the time duration (s) of a plume segment traversing the fine spatial element as given in Equation (2-33), and

- *SFI* is the inhalation protection factor (dimensionless), as specified by the parameter PROTIN.

The off-centerline correction factor, Y, depends on whether the person is stationary or evacuating. When stationary, Y is the standard off-centerline correction factor, *J*, which depends on the amount of lateral dispersion and the lateral distance from the fine spatial element to the plume centerline. When evacuating, Y is the top-hat correction factor, *U*. Evacuees are either inside the plume $(U = 0.836)$ or outside the plume $(U = 0)$. See Section 3.2 for more information.

The inhalation dose coefficient DCI_{ik} (*Sv/Bq-inhaled*) for radionuclide *i* and organ *k* is given in the DCF file. Dose coefficients for inhalation are based on the assumed activity median aerodynamic diameter and clearance class, which are typically identified in the DCF file.

3.3.4 Resuspension Inhalation

The inhalation dose during the early phase from resuspended radionuclides after passage of a plume segment is calculated for each of the fine spatial elements using the following equation:

$$DR_k = \left(\sum_i DCI_{ik} \cdot GC_i \cdot RF_i \right) \cdot BR \cdot Y \cdot SFI \quad \textbf{(3-13)}$$

Where

- DR_k is the resuspension inhalation dose (*Sv*) to organ *k* after passage of a plume segment over a fine spatial element,
- DCI_{ik} is the inhalation dose coefficient (*Sv/Bq-inhaled*) of either acute or lifetime dose to organ *k* for radionuclide i, supplied in the DCF file,
- GC_i is the ground concentration (Bq/m^2) of radionuclide i under the plume centerline at the time that the plume leaves the fine spatial element, as calculated by the atmospheric transport model,
- RF_i is the time-integrated resuspension factor (*s/m*) defined below,
- *RC* is the resuspension coefficient that relates ground concentration to air concentration (m^{-1}), specified by the parameter RESCON,
- *BR* is the breathing rate (m^3/s), as specified by BRRATE,
- Y is the off-centerline correction factor (dimensionless) of the fine spatial element, defined in Section 3.2, and
- *SFI* is the inhalation protection factor (dimensionless), as specified by the parameter PROTIN.

The off-centerline correction factor, Y, depends on whether the person is stationary or evacuating. When stationary, Y is the standard off-centerline correction factor, *J*, which depends on the amount of lateral dispersion and the lateral distance from the fine spatial element to the plume centerline. When evacuating, Y is the top-hat correction factor, *U*. Evacuees are either inside the plume ($U = 0.836$) or outside the plume ($U = 0$). See Section 3.2 for more information.

The resuspension factor RF_i for resuspension inhalation is like the integrated exposure factor IEF_i for groundshine, in that both account for the changing dose rate over the length of the exposure period. The resuspension factor also includes a term accounting for the concentration ratio between the air and ground. For the early phase, the resuspension factor RF_i is calculated using the following equation:

$$RF_i = RC \cdot \int_{t_1}^{t_2} e^{-\lambda_i t} \cdot e^{-\lambda_r t} dt \tag{3-14}$$

Where

- *RC* is the resuspension coefficient that relates ground concentration to air concentration (m^{-1}), specified by the parameter RESCON,
- λ_i is the radioactive decay constant of radionuclide i,
- λ_r is the resuspension weathering decay constant (s^{-1}) for the early phase, where $\lambda_r = \frac{ln(2)}{t_{1/2}}$, and $t_{1/2}$ is the resuspension half-life (s) specified by the parameter RESHAF, and
- t_1 and t_2 are the times that people enter and leave a spatial element after the plume passage.

Equation (3-14) is an illustrative example for cases of simple decay with no ingrowth, although MACCS also accounts for ingrowth as well. As before, the values of t_1 and t_2 depend on the emergency response scenario, discussed in Section 4.2.

MACCS only calculates the resuspension inhalation dose after plume passage. During the passage of a plume, resuspension represents only a small fraction of the total inhalation dose and is ignored. The resuspension weathering equation in Equation (3-14) is similar to the one used in the intermediate and long-term phases, but it is simpler in that it uses a single resuspension coefficient and resuspension half-life. Resuspension in the intermediate and long-term phases can use up to a three-term expression for the resuspension factor.

3.3.5 Skin Deposition

Exposed skin for people directly immersed in a radioactive cloud may be contaminated as a result of material deposited by the cloud. If this material remains on the skin, there is a potential for damage to the skin.

In MACCS, skin deposition is only used to calculate the acute skin dose, and no other pathway contributes to this dose. Unlike other exposure pathways, MACCS does not consider the contribution of skin deposition to lifetime doses for cancer risk or to the effective dose, and MACCS assumes skin deposition doses to other organs are negligible.

In calculating the acute dose from skin deposition, MACCS assumes that material is deposited from the cloud to skin using a fixed dry deposition velocity of 0.01 *m/s*. For a given plume segment, the skin dose during the plume passage is calculated for each of the fine spatial elements using the following equation:

$$DS = \left(\sum_i DCS_i \cdot \chi_i^G\right) \cdot V_d \cdot Y \cdot F \cdot SFS \tag{3-15}$$

Where

- DS is the acute dose (*Sv*) from skin deposition during passage of a plume segment over a fine spatial element,
- DCS_i is the acute skin dose coefficient (*Sv-m*^{2}/*Bq*) from skin deposition for radionuclide *i*, defined below,
- χ_i^G is the time-integrated ground-level air concentration (*Bq-s/m*^{3}) of radionuclide *i* under the plume centerline, as calculated by the atmospheric transport model in Equation (2-58),
- V_d is the deposition velocity to skin (*m/s*), which in the code is a fixed value of 0.01 *m/s*,
- *Y* is the off-centerline correction factor (dimensionless) discussed below,
- *F* is the fraction of exposure duration during the plume passage, equal to *TE/TO*; where *TE* is the exposure time(s) of an individual at the fine spatial element and *TO* is the time duration(s) of a plume segment over the fine spatial element, and
- *SFS* is the skin dose protection factor dimensionless), specified by SKPFAC.

The off-centerline correction factor, *Y*, depends on whether the person is stationary or evacuating. When stationary, *Y* is the standard off-centerline correction factor, *J*, which depends on the amount of lateral dispersion and the lateral distance from the fine spatial element to the plume centerline. When evacuating, *Y* is the top-hat correction factor, *U*. Evacuees are either inside the plume ($U = 0.836$) or outside the plume ($U = 0$). See Section 3.2 for more information.

MACCS calculates the skin deposition dose coefficient, DCS_i, in the code internally, based on the following assumptions:

(1). Every radioactive disintegration of material deposited on the skin results in the emission of a single beta particle,

(2). There is no buildup of radioactive daughter products on the skin subsequent to the initial deposition of material, and

(3). All material deposited on the skin remains there for eight hours following its deposition.

For multiple plume segment releases, the acute skin dose from each segment is accumulated independently. It is assumed that the radioactive materials deposited on the skin would be removed eight hours after deposition by decontamination procedure. Therefore, accumulation of the skin dose from each plume segment is terminated eight hours after its deposition.

Because of the limited ability of beta radiation to penetrate skin, the dose rapidly decreases with increasing distance from the surface. The dose in the immediate surface layer is not pertinent since the outermost skin cells are dead and, therefore, are insensitive to damage. The rapidly dividing basal cells below 0.09 mm are deemed most sensitive to damage (Evans, 1990). Therefore, MACCS considers the dose received by the tissue at this depth.

According to Healy (1984), at the critical depth of human skin, the dose rate from material deposited on the skin surface does not show a significant variability over a range of decay energy from 0.2 to 2.0 MeV. For emissions in this range of energy, the dose rate at the critical depth of skin is roughly 0.2 rads/s for skin contaminated to a unit concentration of 1 Ci/m^2. Assuming a RBE of 1 for β particles and converting to SI units, this is equivalent to a dose rate coefficient of 5.4×10^{-14} $Sv\text{-}m^2/Bq\text{-}s$.

The skin dose coefficient DCS_i ($Sv\text{-}m^2/Bq$) in Equation (3-15) is then calculated using the following equation,

$$DCS_i = DRCS_i \cdot \int_0^T e^{-\lambda_i t} dt = DRCS_i \cdot \frac{1.0 - e^{-\lambda_i T}}{\lambda_i} \tag{3-16}$$

Where

- $DRCS_i$ is the acute skin dose rate coefficient from skin deposition, which in MACCS has a fixed value of 5.4×10^{-14} $Sv\text{-}m^2/Bq\text{-}s$,
- λ_i is the decay constant (s^{-1}) of radionuclide i, and
- T is the residence time (s) of radionuclide material on the skin, assumed to be eight hours.

3.4 Late Doses

MACCS divides the calculation of radiation doses into two domains: early doses (from exposures during and shortly after plume passage) during the early phase and late doses during the intermediate and long-term phases. MACCS calculates late doses when the user provides a value of “FALSE” to both MACCS parameters ENDAT1 and ENDAT2, which are the parameters that would skip the EARLY and CHRONC modules, respectively.

MACCS calculates late doses for each coarse spatial element with ground deposition. Late doses include four dose exposure pathways: (1) groundshine, (2) resuspension inhalation, (3) food ingestion, and (4) water ingestion.

The “direct” late pathways are the groundshine and resuspension inhalation doses. In MACCS, food ingestion and water ingestion are “indirect” pathways. Because of additional transport of food and water, ingestion doses do not necessarily occur in the spatial element where deposition occurs, and MACCS does not attempt to model the actual location of the receptor. For this reason, ingestion doses are only included in collective consequence metrics, whereas, groundshine and resuspension inhalation pathways contribute to both individual and collective consequence metrics. MACCS also estimates doses to decontamination workers (from groundshine only). Like ingestion, worker doses only contribute to collective consequence metrics. For these reasons, the tallies of collective consequence metrics are a more complete measure of consequence than individual consequence metrics, as individual metrics are based on a partial set of dose contributions.

The late dose D_k^L to organ *k* for an individual in a given spatial element is the following:

$$D_k^L = DG_k^L + DR_k^L \tag{3-17}$$

Where

- D_k^L is the late dose (*Sv*) to organ *k* in an individual from the combined intermediate and long-term phases,
- DG_k^L is the late dose (*Sv*) to organ *k* in an individual from groundshine from the combined intermediate and long-term phases,
- DR_k^L is the late dose (*Sv*) to organ *k* in an individual from resuspension inhalation from the combined intermediate and long-term phases,

As discussed, the tally for the individual dose does not include the "indirect" pathways of food and water ingestion, and does not include doses to decontamination workers. These contributions are included in the population dose.

The late population dose $D_k^{L,POP}$ (*person-Sv*) to organ *k* in a given spatial element from the combined intermediate and long-term phases is the following:

$$D_k^{L,POP} = D_k^L \cdot POP + DF_k + DW_k + DWD_k \tag{3-18}$$

Where

- D_k^L are the late doses (*Sv*) considered in the dose tally for individual residents in a given spatial element discussed above,
- POP is the population of individual residents in a given spatial element
- DF_k is the population dose (*person-Sv*) from food ingestion to organ *k* resulting from the deposition onto farmland of the spatial element,
- DW_k is the population dose (*person-Sv*) from water ingestion to organ *k* from deposition in a spatial element,
- DWD_k is the worker population dose (*person-Sv*) to organ *k* for performing decontamination in a spatial element,

Groundshine and resuspension inhalation doses occur during both the intermediate phase and long-term phase, unless otherwise interdicted. The two phases have separate interdiction criteria. In the intermediate phase, spatial elements are either interdicted for the full period or not at all. In the long-term phase, dose calculation begins when land is first occupied and continues for a user-specified period (EXPTIM). If there is a period of interdiction, the dose calculation begins when people return. If people are not able to return because their land is condemned, there is no dose to those individuals in the long-term phase.

For the food and water ingestion pathways, transport of deposited radionuclides into the food and drinking water supply begins when the early phase ends. MACCS assumes that all drinking water is below interdiction levels, and therefore there is no drinking water interdiction. If there is a period of farmland interdiction, no food ingestion dose occurs until the land becomes farmable. There is no food ingestion dose from farmland that is permanently interdicted (i.e., condemned). The intake duration for the drinking water pathway and the original food-chain model pathway is endless. The last year that intake can occur in the COMIDA2 food-chain model is set by the COMIDA2 input parameter LASTACUM.

For decontamination worker doses, the dose calculation starts at the beginning of decontamination (which MACCS assumes is the beginning of the long-term phase) and continues for a user-specified period of TIMDEC. There is no decontamination worker dose in areas with no decontamination.

Like early doses, late dose equations depend on ground concentration, dose coefficients, protection factor, exposure period, and potentially other pathway-specific factors.

Late dose equations can calculate lifetime or annual doses. MACCS does not calculate acute doses as it does for early exposures because it assumes that exposures are small and do not contribute to early health effects after the early phase. MACCS calculates lifetime doses and annual doses using the same late dose equations. To calculate annual doses, MACCS discretizes the exposure period into yearly periods. Also, because dose coefficients for internal pathways are based on a commitment period, MACCS requires a dose coefficient for each year of the commitment period to calculate an annual dose. MACCS uses the same external dose coefficients for lifetime doses and annual doses.

Like the early phase, MACCS uses an off-centerline correction factor and ground concentration under the plume centerline to estimate the initial ground concentration for spatial elements. However, this is done for the coarse spatial elements instead of the fine spatial elements. Section 3.2 discusses the off-centerline factors for the late dose equations.

3.4.1 Groundshine

The groundshine dose DG_k to organ k for the intermediate or long-term phase is calculated for each of the coarse spatial elements using the following equation:

$$DG_k = \left(\sum_i DRCG_{ik} \cdot GC_i \cdot IEF_i \right) \cdot SFG \quad \textbf{(3-19)}$$

Where

- $DRCG_{ik}$ is the groundshine dose rate coefficient (*Sv-m*^{2}*/Bq-s*) to the organ k for the radionuclide i, supplied in the DCF file,

- GC_i is the ground concentration (*Bq/m*^{2}) of radionuclide i in the spatial element, calculated by Equation (3-7),

- IEF_i is the integrated exposure factor (s) for radionuclide i discussed below, and

- SFG is the groundshine shielding factor (dimensionless), specified by the parameter LGSHFAC.

The form of Equation (3-19) is very similar to Equation (3-10) representing early phase groundshine, except that the ground concentration for the intermediate and long-term phase already account for the off-centerline correction factor.

Additionally, the groundshine integrated exposure factor IEF_i for the intermediate and long-term phase is like the integrated exposure factor for the early phase, in that both account for the changing dose rate over the length of the exposure period. However, in addition to decay and ingrowth, late groundshine doses may be further reduced due to decontamination and natural weathering processes. The integrated exposure factor IEF_i for late groundshine doses is as follows:

$$IEF_i = \frac{1}{DRF_\ell} \cdot \int_{t_1}^{t_2} e^{-\lambda_i t} \cdot Gw(t) dt \qquad \textbf{(3-20)}$$

Where

- DRF_ℓ is the dose reduction factor (dimensionless) for decontamination level (ℓ) when decontamination occurs, as specified by the parameter $DSRFCT_\ell$,
- t_1 and t_2 are the start and end of the exposure period,
- λ_i is the radioactive decay constant (s^{-1}) of radionuclide i, and
- $Gw(t)$ is Gale's groundshine weathering function (dimensionless), defined below.

The dose reduction factor, DRF_ℓ, is the effectiveness of decontamination and only applies in Equation (3-20) when decontamination is performed. MACCS assumes decontamination only occurs during the long-term phase, and the use of the dose reduction factor, DRF_ℓ, in the dose calculation depends on the decontamination model discussed in Section 4.4.1.

Equation (3-20) is an illustrative example for cases of simple decay with no ingrowth, although MACCS also accounts for ingrowth as well. The times t_1 and t_2 are relative to the ground concentration GC_i at the end of the early phase. Before calculating the groundshine dose to an individual, the model first determines whether protective actions should be taken. Intermediate phase actions only account for interdiction. Long-term phase actions can include decontamination, decontamination plus additional interdiction, or condemnation of land.

For intermediate phase, integration period in Equation (3-20) is the beginning and end of the intermediate phase, that is:

- $t_1 = 0$
- t_2 = DUR_INTPHAS

Where DUR_INTPHAS is parameter for the duration of the intermediate phase. MACCS does not consider return of displaced individuals during the intermediate phase, and so the exposure period is either the full duration of the intermediate phase or zero. If DUR_INTPHAS is zero, or if no intermediate phase interdiction occurs, the intermediate phase dose is calculated to be zero.

For the long-term phase, the integration period in Equation (3-20) is:

- t_1 = DUR_INTPHAS + t_3
- $t_2 = t_1$ + EXPTIM

Where

- EXPTIM is the MACCS parameter for the long-term exposure period, and
- t_3 is the long-term phase interdiction period.

If condemnation occurs, the long-term phase dose is calculated to be zero. The length of interdiction t_3 depends on the protective actions. For the model to determine which protective actions to take, the model must compare the sum of the projected intermediate or long-term groundshine and resuspension doses (assuming no protective actions) to a dose criterion, that is, a dose level that would require protective actions. Section 4 discusses the protective action models in more detail.

Gale's equation (Gale, Miller, & Fisher, 1964) for the decrease in radiation levels in the ambient environment due to natural weathering processes is a two-term exponential decay function shown by the following equation:

$$Gw(t) = WC_1 \cdot e^{-\lambda_1 t} + WC_2 \cdot e^{-\lambda_2 t} \quad \textbf{(3-21)}$$

Where

- WC_1 and WC_2 are the weathering coefficients (dimensionless), as specified by GWCOEF, and
- λ_1 and λ_2 are the weathering decay constants (s^{-1}), where $\lambda = \frac{ln(2)}{t_{1/2}}$, and $t_{1/2}$ is the resuspension half-life (s) specified, as specified by TGWHLF.

By combining Equations (3-19), (3-20), and (3-21), the model calculates the groundshine dose between two specified times t_1 and t_2. For example, in the intermediate phase, t_1 could be the end of the early phase, and t_2 could be the end of the intermediate phase if no relocation is needed for a given spatial element.

3.4.2 Resuspension Inhalation

The dose DR_k from inhalation of resuspended radionuclides to organ *k* during the intermediate or long-term phase is calculated for each of the coarse spatial elements using the following equation:

$$DR_k = \left(\sum_i DCI_{ik} \cdot GC_i \cdot RF_i\right) \cdot BR \cdot Y \cdot SFI \quad \textbf{(3-22)}$$

Where

- DCI_{ik} is the inhalation dose coefficient (*Sv/Bq-inhaled*) for either acute or lifetime dose to organ *k* for radionuclide *i*, supplied in the DCF file,
- GC_i is the initial ground concentration (*Bq/m*^{2}) of radionuclide *i* in a spatial element, calculated by Equation (3-7),
- RF_i is the time-integrated resuspension factor (*s/m*) defined below,
- BR is the breathing rate (*m*^{3}*/s*), specified by the parameter LBRRATE,
- SFI is the inhalation protection factor (dimensionless), specified by the parameter LPROTIN, and

The form of Equation (3-22) is very similar to Equation (3-13) for early phase resuspension inhalation except that the ground concentration for the intermediate and long-term phase already account for the off-centerline correction factor.

The resuspension factor RF_i for the intermediate and long-term phase is calculated using the following equation:

$$RF_i = \frac{1}{DRF_\ell} \cdot \int_{t_1}^{t_2} \left(\sum_{m=1}^{3} RC_m \cdot e^{-\lambda_m t}\right) \cdot e^{-\lambda_i t} dt \quad \textbf{(3-23)}$$

Where

- DRF_ℓ is the dose reduction factor (dimensionless) for decontamination level (ℓ) when decontamination occurs, as specified by the parameter $DSRFCT_\ell$,
- t_1 and t_2 are the start and end of the exposure period (*s*),
- RC_m is the resuspension weathering coefficient (*m*$^{-1}$) for the m^{th} term, specified by the parameter $RWCOEF_m$,
- λ_m is the resuspension weathering decay constant (*s*$^{-1}$), where $\lambda = \frac{ln(2)}{t_{1/2}}$, and $t_{1/2}$ is the resuspension half-life (*s*) specified by the parameter $TRWHLF_m$, and
- λ_i is the decay constant (*s*$^{-1}$) of radionuclide *i*,

The dose reduction factor, DRF_{ℓ}, is the effectiveness of decontamination and only applies in Equation (3-22) when decontamination is performed. MACCS assumes decontamination only occurs during the long-term phase, and the use of the dose reduction factor, DRF_{ℓ}, in the dose calculation depends on the decontamination model discussed in Section 4.4.1.

Equation (3-23) is an illustrative example for cases of simple decay with no ingrowth, although MACCS also accounts for ingrowth as well. Just as it is for late groundshine doses, the times t_1 and t_2 that indicate when people occupy a spatial element depend on the protective actions during the intermediate or long-term phase. See Section 3.4.1 on late groundshine doses for more information.

The resuspension factor RF_i for early resuspension inhalation in Equation (3-14) and for late resuspension inhalation in Equation (3-23) are similar in that both account for the changing dose rate over the length of the exposure period and both account for the concentration ratio between the air and ground. However, for late exposures, MACCS considers three resuspension weathering terms instead of a single term in the early phase.

By combining Equations (3-22) and (3-23), the inhalation dose of resuspended radionuclides in the intermediate or long-term phase can be calculated for a time period of interest.

3.4.3 Food Ingestion

MACCS has two food ingestion models. The user can choose the COMIDA2 food-chain model by giving the MACCS parameter FDPATH a value of "NEW," or the original food-chain model by using a value of "OLD." A value of "OFF" turns off both models. If the user turns off both models, MACCS does not calculate ingestion doses, from either food or drinking water pathways. The original food model is not available when using the annual-threshold or piecewise-linear dose-response model (i.e., DOSMOD = "AT" or "PL").

Contamination of food (and water) results from the dry and wet deposition of the radioactive plume as it is carried from the accident site downwind. Both food-chain models assume food ingestion doses come only from contaminated farmland. The transport of deposited radionuclides into the food supply begins when the early phase ends.

The food ingestion dose calculated by MACCS is a population dose (*person-Sv*). The COMIDA2 food chain also calculates an annual individual food ingestion dose (*Sv*) as an input to the protective action models. MACCS tabulates ingestion doses for the area over which the radioactive plume deposits radioactive material rather than the area where people that receive the dose reside.

3.4.3.1 COMIDA2 Food-Chain Model

COMIDA2 is a preprocessor external to MACCS that generates annual ingestion dose coefficients for a list of organs, radionuclides, crop types, seasons, and exposure years in a binary file. COMIDA2 generates food-chain modeling results based on the ingestion dose coefficients in the MACCS DCF file, radionuclide data, consumption and production rates, transfer rates, animal and vegetation data, and other parameters. The user must use the same DCF file in COMIDA2 as in MACCS to perform a calculation. More information on COMIDA2 can be found in

NUREG/CR-6613 Vol.2 (Chanin & Young, 1998b) and the COMIDA model report (Abbott & Rood, 1993; Abbott & Rood, 1994).

The population dose for food ingestion using the COMIDA2 food-chain model is as follows:

$$DF_k = \left(\sum_i DCFI_{ik} \cdot GC_i\right) \cdot A \cdot FF \tag{3-24}$$

Where

- DF_k is the population dose (*person-Sv*) from food ingestion to organ *k* resulting from the deposition onto farmland for a spatial element,

- $DCFI_{ik}$ is the ingestion dose coefficient (*person-Sv-m*$^{-2}$/*Bq-m*$^{-2}$) to organ *k* for radionuclide *i* through all crop pathways, as defined below,

- GC_i is the concentration of radionuclide *i* in a spatial element (*Bq/m*^{2}), calculated by Equation (3-7),

- A is the land area of the spatial element, as calculated by MACCS from the grid definitions times the fraction of the grid that is land, and

- FF is the farmland fraction of land area, as derived either from the site data file, or from the land fraction (FRACLD) and farm fraction parameters (FRCFRM).

There is no protection factor for ingestion doses, i.e., it is assumed to be unity. In MACCS, there is also no reduction based on decontamination. Nevertheless, decontamination may still affect food ingestion doses, as decontamination can help restore habitability, and habitability is one of the criteria used in farming restrictions (see Section 4.4.2).

The ingestion dose coefficient $DCFI_{ik}$ (*person-Sv-m*$^{-2}$/*Bq-m*$^{-2}$) to organ *k* for radionuclide *i* is the following:

$$DCFI_{ik} = \sum_{j=n}^{N} DCFI_{ijk} \tag{3-25}$$

Where

- $DCFI_{ijk}$ is the annual population ingestion dose coefficient (*person-Sv-m*$^{-2}$/*Bq-m*$^{-2}$) to organ *k* from exposures in year *j* for radionuclide *i* through all crop pathways and for the specific season, supplied by the COMIDA2 file.

- {*n*, ..., *N*} is the set of years *j* that food ingestion occurs, where *n* is the first year after the accident that farming occurs, and *N* is the last year of the ingestion exposure period, as specified by the COMIDA2 parameter LASTACUM.

The annual population ingestion dose coefficient, $DCFI_{ijk}$, is for the annual period beginning at the end of the early phase, which is different than the start of the farm year. COMIDA2 calculates the dose for different crop seasons, and automatically apportions this dose into annual periods of the accident.

COMIDA2 binary file can contain many seasonal sets of annual ingestion dose coefficients $DCFI_{ijk}$. The COMIDA2 parameter NUMDATES specifies the number of seasons ℓ, and the COMIDA2 parameter ACCDATES$_\ell$ specifies the Julian day of the year that season ℓ begins. MACCS selects the set of dose coefficients appropriate for the season that release occurs, specifically according to the day that the MAXRIS plume segment is released.

The food ingestion restrictions model determines the number of farm interdiction years (see Section 4.4.2). When farmland is not interdicted ($n=1$), the end of the early phase period (ENDEMP) defines the beginning of the ingestion exposure period. The last year of the ingestion exposure period (LASTACUM) does not depend on the number of farm interdiction years. For example, when farmland interdiction is lifted in year 3, and LASTACUM has a value of 9, population ingestion doses are accrued for the period denoted as years 3 to 9. If the number of farm interdiction years is equal or greater than the last year of the ingestion exposure period ($n > N$), there is no food ingestion dose. This is different than the long-term exposure period for individuals (EXPTIM), which is a period that begins when people return to their property in the long-term phase.

MACCS also calculates three food ingestion dose projections to an individual (assuming no protective action). The farming restrictions model uses these calculations to determine whether this dose projection exceeds a protective action limit. Typically, dose projections use a dose equation that is already available. However, since MACCS does not otherwise use individual food ingestion doses, this is a special case.

The three dose projections are the annual food ingestion dose DF_{jk} in year *j* to organ *k*, the first-year milk dose DF_k^M to organ *k*, and the first-year non-milk dose DF_k^{NM} to organ *k*. MACCS calculates these three dose projections and compares them against user-specified farmability criteria in the parameters DOSELONG, DOSEMILK, and DOSEOTHR, respectively. This is discussed in more detail in Section 4.4.2.2.

The annual food ingestion dose to an individual is as follows:

$$DF_{jk} = \sum_i DCFI_{ijk} \cdot GC_i \tag{3-26}$$

Where

- DF_{jk} is the annual dose (*Sv*) from food ingestion exposures in year *j* to organ *k* through all crop pathways resulting from the deposition onto farmland of the spatial element,

- $DCFI_{ijk}$ is the annual ingestion dose coefficient (*Sv-m*^{2}/*Bq*) to organ k from exposures in year *j* for radionuclide *i* through all crop pathways and for the specific season, supplied by the COMIDA2 binary file, and

- GC_i is the concentration of radionuclide i in a spatial element (*Bq/m*^{2}), calculated by Equation (3-7).

Because the individual food ingestion doses are only used for protective action modeling, COMIDA2 does not calculate dose coefficients for all organs, but rather just the thyroid and the whole-body effective dose.

The first-year milk and non-milk doses to an individual are as follows:

$$DF_k^M = \sum_i DCFI_{ik}^M \cdot GC_i \tag{3-27}$$

and

$$DF_k^{NM} = \sum_i DCFI_{ik}^{NM} \cdot GC_i \tag{3-28}$$

Where

- DF_k^M and DF_k^{NM} are the first-year doses (*Sv*) from dairy food ingestion and non-dairy food ingestion, respectively, resulting from the deposition onto farmland of the spatial element,

- $DCFI_{ik}^M$ and $DCFI_{ik}^{NM}$ are the first-year dairy and non-dairy ingestion dose coefficients (*Sv-m*^{2}/*Bq*), respectively, to organ *k* for radionuclide *i* considering the respective fraction of the crop pathways applicable to dairy and non-dairy food products and for the specific season, supplied by the COMIDA2 binary file, and

- GC_i is the concentration of radionuclide i in a spatial element (*Bq/m*^{2}), calculated by Equation (3-7).

As done for the annual food ingestion dose to an individual, COMIDA2 does not calculate dose coefficients for all organs, but rather just the thyroid and the whole-body effective dose.

3.4.3.2 Original Food-Chain Model

When radioactive material is deposited onto farmland, an ingestion dose to the population can result from two pathways: (1) a growing season pathway resulting primarily from the direct deposition of radionuclides onto the growing crops and (2) a long-term pathway resulting from root uptake and soil ingestion by animals of the material from contaminated soil. The growing season pathway is further divided into a milk and a non-milk pathway. Therefore, the total food ingestion dose is as follows:

$$DF_k = DF_k^M + DF_k^{NM} + DF_k^{LT} \tag{3-29}$$

Where

- DF_k is the population dose (*person-Sv*) from food ingestion to organ *k* resulting from the deposition onto farmland of the spatial element,

- DF_k^M is the growing season population ingestion dose to organ *k* (*person-Sv*) via milk ingestion,

- DF_k^{NM} is the growing season population ingestion dose to organ *k* (*person-Sv*) via non-milk ingestion,

- DF_k^{LT} is the long-term ingestion population dose to organ *k* (*person-Sv*), which is food grown after the start of the accident.

Doses from the growing season only occur if the accident occurred during the growing season. All variables in the equations for these food ingestion pathways except the ground concentration are user supplied or are derived from user-supplied data. Three input files supply food pathway data for the MACCS code: the site data file, the DCF file, and the CHRONC user input file. For a description of these files, consult the MACCS User's Guide (SAND-2021-1588). The population dose to any organ is determined by summing the derived doses over all the radionuclides and all crops for all exposure years.

Separating the ingestion doses in this manner allows MACCS to model direct contamination of crops in the current growing season differently than those for future seasons. The growing season pathway can contaminate only those crops being grown at the time of the accident. The resulting dose to the population depends on the day in the year when the accident occurs. If the accident occurs outside the growing season, there is no resulting dose from the growing season pathway. In contrast, the long-term root uptake of radioactive material into food products may span many successive growing seasons. The dose resulting from the long-term pathway is independent of the time of the year when the accident occurs.

For both pathways, the material is transferred to the population via three mechanisms:

(1). direct consumption of the crop by the population,

(2). consumption of milk produced by animals that have consumed radioactive material, and

(3). consumption of meat from animals that have consumed radioactive material.

The ingestion model does not attempt to ascertain the specific amount of radioactive material consumed by any individual, but rather determines the total amount of the material ultimately consumed by the population. The resulting health effects are therefore attributed to society as a whole. There is no provision in the model for examination of the ingestion dose incurred by specific individuals.

The original food-chain model divides farming activities into four components representing two sets of binary pairs:

- MILK DIRECT-DEPOSITION
- CROP DIRECT-DEPOSITION
- MILK ROOT-UPTAKE
- CROP ROOT-UPTAKE

MILK refers to both fresh milk as well as to dairy products such as cheese and butter. CROP refers to all other foodstuffs. DIRECT-DEPOSITION refers to doses that result when an accident occurs during the growing season. MACCS assumes these doses are incurred in the single annual period following the accident. If an accident occurs outside of the growing season, the code does not evaluate the need for disposal of growing crops, and the corresponding doses from the milk and crop pathways are reported as zero. In contrast, ROOT-UPTAKE refers to food doses that result irrespective of whether the accident occurs during the growing season, begins the first year that there is no farm interdiction following the accident, and has an endless dose exposure period (i.e., an integration period with an endpoint of *t*=infinity). These two periods may overlap. That is, for accidents that occur during the growing season, doses may be incurred from *both* the direct-deposition and root-uptake components of the original food-chain model.

Long-term Ingestion Dose

Each year that there are no farming or habitation restrictions, an ingestion dose due to farmland contamination can result from that spatial element. The long-term ingestion dose received from radionuclide *i* through root uptake and soil ingestion by animals is the product of the long-term transfer factor from the soil to humans, the ground concentration in that grid element, the area in the grid element devoted to farming, a weathering and decay term that reflects the losses from possible temporary interdiction, and the ingestion dose coefficient. The long-term dose commitment to any organ *k* is determined as follows:

$$DF_k^{LT} = \sum_i \left(DCW_{ik} \cdot GC_i \cdot e^{-\lambda_i t} \cdot FA \cdot \sum_j \left(FAC_j \cdot TF_{ij} \right) \right) \qquad \textbf{(3-30)}$$

Where

- DF_k^{LT} is the long-term ingestion population dose (*person-Sv*) to organ *k* from a spatial element,
- DCW_{ik} is the ingestion dose coefficient (*person-Sv*/*Bq-ingested*), supplied by the DCF file,
- GC_i is the initial ground concentration (*Bq*/*m*^{2}) of the food ingestion radionuclides *i*, defined by the set of radionuclides in the parameter NAMIPI,
- t is the number of years during which temporary interdiction occurs (*yr*), as determined by the long-term ingestion restrictions model (see Section 4.4.2),

- λ_i is the weathering and radiological decay constant (yr^{-1}) for radionuclide i, user-specified input data as QROOT,

- FA is the area (m^2) of farmland contained in the spatial element being considered,

- FAC_j is the user-specified fraction (dimensionless) of the farmland area devoted to the growing of crop j, as specified by $FRCTFL_j$, and

- TF_{ij} is the long-term overall transfer factor (dimensionless) for radionuclide i to population via crop j, calculated by Equation (3-40).

Equation (3-31) is an illustrative example for cases of simple decay with no ingrowth, although MACCS also accounts for ingrowth as well.

<u>Milk Ingestion Dose from Current Growing Season</u>

When the accident occurs during the growing season and there is no milk disposal, the ingestion dose from the milk pathway during the first growing season is calculated. The population dose to any organ k via the direct milk pathway during the first year is the sum of the doses received from all the food ingestion radionuclides. This dose is defined as follows:

$$DF_k^M = \sum_i \left(DCW_{ik} \cdot GC_i \cdot FA \cdot \sum_j \left(FAC_j^M \cdot TF_{ij}^M \right) \right) \qquad \textbf{(3-31)}$$

Where

- DF_k^M is the growing season population ingestion dose (*person-Sv*) to organ k via milk pathway from a spatial element,

- FAC_j^M is the fraction of the farmland area devoted to the growing of crop j, as specified by $FRCTFL_j$, which in this case is pasture,

- TF_{ij}^M is the overall transfer factor for radionuclide-crop pair (i,j), that is, the fraction of the material deposited on farmland during the growing season that is ultimately consumed by humans in the form of milk products, calculated by Equation (3-39), and

- DCW_{ik}, GC_i, and FA are the same as previously defined.

<u>Non-milk Ingestion Dose from Current Growing Season</u>

When the accident occurs during the growing season and there is no non-milk crop disposal, the ingestion population dose from the non-milk pathways during the first year is calculated. The population dose to any organ k via the growing season non-milk pathways during the first growing season is the sum of the dose received from each of the food ingestion radionuclides. It is defined as follows:

$$DF_k^{NM} = \sum_i \left(DCW_{ik} \cdot GC_i \cdot FA \cdot \sum_j \left(FAC_j^{NM} \cdot TF_{ij}^{NM} \right) \right) \quad \textbf{(3-32)}$$

Where

- DF_k^{NM} is the growing season population ingestion dose (*person-Sv*) to organ *k* via non-milk pathway from a spatial element,
- FAC_j^{NM} is the fraction of farmland area devoted to non-milk crop *j*, as specified by FRCTFL_j,
- TF_{ij}^{NM} is the overall transfer factor for radionuclide-crop pair (*i*,*j*), that is, the fraction of the material deposited on farmland during the growing season that is ultimately consumed by humans in the form of non-milk products, calculated by Equation (3-39), and
- DCW_{ik}, GC_i, and FA are the same as previously defined.

Food Pathways Transfer Factors

At the heart of the food pathways model in the MACCS code is the determination of the fraction of the radioactive material deposited onto farmland that is ultimately consumed by the population. The food pathways model relates to the food pathways protective actions model described in Section 4.4.2.1. The MACCS ingestion model assumes that it is always possible for the protective actions to reduce individual doses below the user-established criteria for maximum allowable radiological exposure of the public. Since these criteria should normally be set well below the threshold dose for inducing any type of acute health effects, only a lifetime dose commitment to the population at large is calculated. Another fundamental assumption in the MACCS ingestion model is the linearity of the dose-response relationship for cancers resulting from ingestion. For a description of the cancer induction model, refer to Section 6.2.

The transfer of radionuclides through the various pathways is affected not only by processes that facilitate their transfer, but also by processes that is in some manner limit the amount actually consumed. The limiting processes considered are:

(1). radioactive decay between time of deposition and time of consumption of contaminated food,

(2). movement of the radionuclides downward through the soil compartment to a depth where it no longer taken up by the plant,

(3). irreversible chemical binding of the radionuclides with the soil that prevents it from being taken up by the plant,

(4). food processing and preparation methods that will discard part of the contaminated portion of food, and

(5). biological filtering of the radionuclides by meat- or milk-producing animals.

It should be noted that when farmland is decontaminated, no provision is made in the calculation of dose received via the food pathway for a possible decrease of food contamination resulting from the decontamination process. It is assumed that farmland decontamination consists of deep plowing to make the area habitable but does not remove the radioactive material from the root zone. Radioactive material is assumed to remain available for uptake into the food supply. In addition, even though washoff is considered in the water ingestion dose calculations, the food pathway dose calculations do not account for washoff as a removal process. These factors may lead to a small overestimation of the dose received via the food pathway.

The food pathway model implemented in the MACCS code is schematically depicted in Figure 3-4. It consists of a series of connected compartments. Between each pair of compartments is a transfer factor that defines the fraction of the radioactive material transmitted from one compartment to the next. In the MACCS code, each of these transfer factors is supplied as user input.

A definition of each transfer factor indicated in the overview of the food pathways is given in Table 3-2. All variables indicated are user-supplied data except for CTD, which is calculated within the code from user-supplied data. The variables TFSI (transfer factor from soil to animals by soil ingestion) and CTR are combined and supplied as the input variable TCROOT.

The current version of the ingestion pathway model has the capability to handle as many as 10 radionuclides and as many as 10 crop categories. Since the definition of the parameters describing the ingestion model is the responsibility of the user, refer to the MACCS User's Guide (SAND-2021-1588) where a sample set of input files is presented. The relevant files are the CHRONC user input file and the site data file.

In the food pathways model, two processes are considered for the uptake of the radioactive material deposited on farmland into the food supply for humans. The material may be deposited directly onto the plant surfaces of the growing crop. For some crops, this results in the direct contamination of the edible portion of that crop, while for others, the edible portions of the plants are contaminated by biological translocation of the contaminants to the edible portions of plants. Alternatively, the material can be deposited onto the soil and subsequently enter the food chain either by being taken up by the plants themselves or by being ingested with soil by grazing animals. Radionuclides deposited onto the soil can be taken up by plants via root uptake or by deposition onto the plant surfaces via resuspension or rain splash.

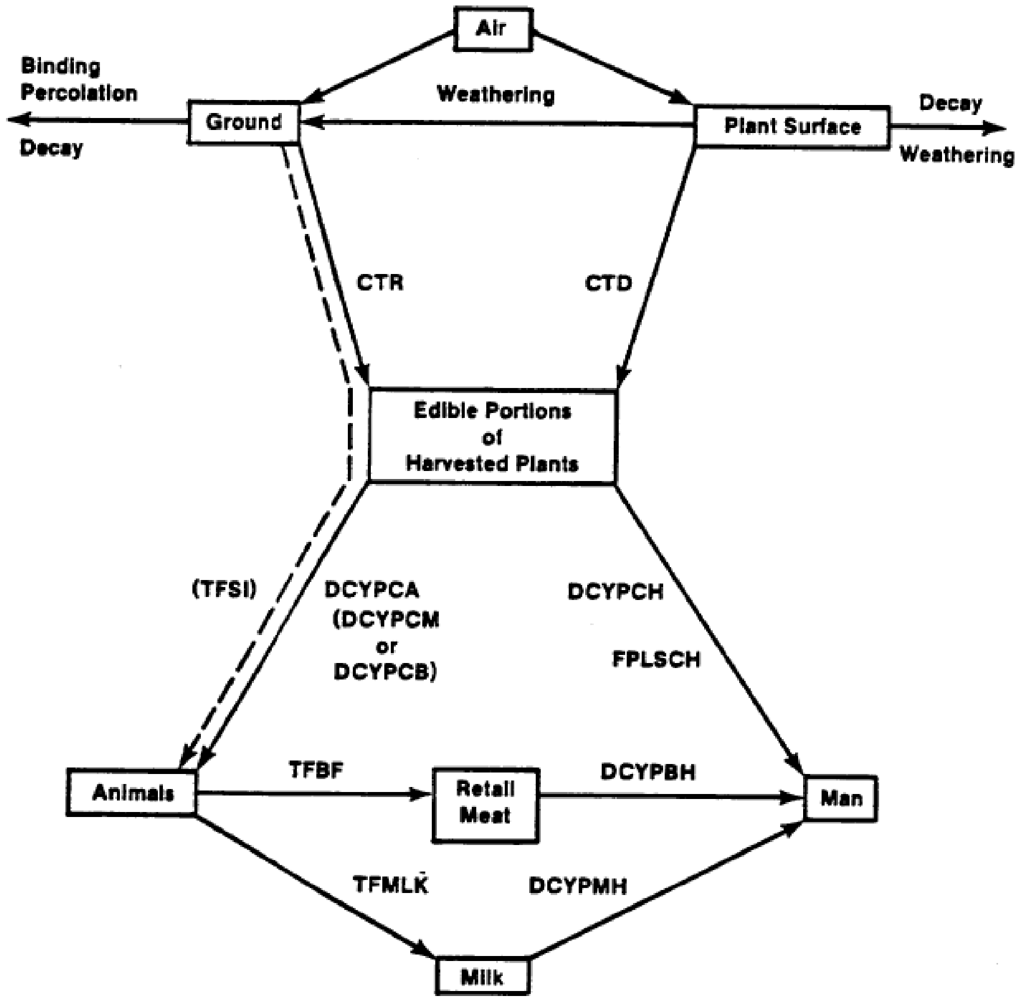

Figure 3-4 Food Pathways in the Original Food-Chain Model

Radioactive material in the edible portions of plants can in turn be transferred to humans by three routes: crop-human, crop-animal-milk-human, and crop-animal-meat-human. For each of these pathways, an overall transfer factor is determined that describes the fraction of the total amount of each radionuclide deposited onto the farmlands that is consumed by humans. These transfer factors are defined for each crop-nuclide pair.

Table 3-2 Glossary of Transfer Factors for Food Pathways Model

Transfer Factor [a]	Relevant Phenomena	Time Delay	
		From	To
CTD	Weathering Radioactive decay	Deposition onto plants	Harvest
DCYPBH	Meat trimming Radioactive decay	Slaughter	Consumption
DCYPCB	Radioactive decay	Harvest	Consumption
DCYPCM	Radioactive decay	Harvest	Consumption
DCYPCH	Radioactive decay	Harvest	Consumption
DCYPMH	Radioactive decay	Production of milk	Consumption
FPLSCH	Food processing Food preparation	Harvest	Consumption
CTR	Radioactive decay Percolation Binding with soil	Deposition onto soil	Harvest
TFBF	Biological filtration Radioactive decay	Feed consumption	Slaughter
TFMLK	Biological filtration Radioactive decay	Feed consumption	Milk production
TFSI	Radioactive decay Binding with soil Percolation	Deposition onto soil of pastureland	Consumption
TCROOT	Radioactive decay Binding with soil Percolation	Deposition	Consumption

[a] All transfer factors are dimensionless.

<u>Transfer of Radionuclides Deposited Directly onto Plant Surfaces</u>

The transfer of directly deposited radionuclides to edible portions of the crop is dependent upon the time of year the accident occurs. When an accident occurs outside the growing season, none of the radioactive material is deposited onto growing crops, and the growing season transfer factor, CTD, is zero. When an accident occurs during the growing season for a given crop, the amount of contamination present in the edible portion of a crop at harvest depends on the point during the growing season when the accident occurs. For most types of crops, harvesting is assumed to occur at the end of the growing season. The important variable for these crops is the length of time between deposition and harvest. For pasture-type crops, continual harvesting over the entire growing season is assumed. The time between the beginning of the growing season and the time of the accident is also important for pasture-type crops.

The direct transfer of contamination to the edible portions of a plant depends on the degree to which the edible portion is exposed to the outside environment. For some crops (e.g., grain) the edible portion of the plant is completely protected from the outside environment, and contamination of the edible portion requires the biological translocation of a radionuclide from the plant surfaces to the edible portions of the plant.

When the edible portion of the plant is exposed, an increase in the duration between deposition and harvest normally results in a decrease in the retention factor from weathering and decay processes. When the edible portion of a crop is unexposed, however, contamination depends on the biological process of translocation, and the transfer of a radionuclide generally increases as the duration between the accident and harvest increases. Translocation is not modeled explicitly in the MACCS code but can be implicitly considered in establishing the values of the variables CTCOEF, the weathering coefficients, and CTHALF, the weathering half-lives. Additional information regarding the variables CTCOEF and CTHALF can be found in the MACCS User's Guide (SAND-2021-1588).

Regarding the categorization of crop types, pasture is treated uniquely within the MACCS model. It is assumed that pasture undergoes continual harvesting over the entire course of the growing season. It is also assumed that the entire pasture crop is consumed by food-producing animals over the course of a single growing season.

The direct deposition transfer factor CTD_{ij} is defined for every radionuclide i and crop category j pair. The number of terms, n, in the crop transfer function is currently limited to three, as specified by the parameter NTTRM [see Equation (3-33)]. The first term represents the portion of the contamination that is removed quickly by weathering processes, and the second and third, if specified, represent the more persistent contamination mechanisms. When considering crops in which the edible portion is not exposed to the environment, the first term of the crop transfer function can be set to a constant, and the second and third terms, if specified, can be set to zero.

For pasture, harvest is assumed to be a continuous process. Therefore, CTD_{ij} is derived by integrating the uptake function from the time of the accident to the end of the growing season. The uptake function is expressed as the grazing rate modified by the weathering loss rate. The grazing rate of pasture is assumed to be constant over the grazing period, (TE_j - TS_j). Therefore, the grazing rate is 1.0/(TE_j - TS_j). The weathering rate is expressed by a three-term exponential decay function. Therefore, the direct deposition transfer factor of radionuclide i via pasture is calculated using the following equation:

$$\begin{aligned} CTD_{ij} &= \frac{1}{TE_j - TS_j} \cdot \sum_{n=1}^{N} \left(CTCOEF_{ijn} \cdot \int_0^T e^{-H_{ijn}t}\, dt \right) \\ &= \frac{1}{TE_j - TS_j} \cdot \sum_{n=1}^{N} \left(CTCOEF_{ijn} \cdot \frac{1 - e^{-H_{ijn}T}}{H_{ijn}} \right) \end{aligned} \quad \textbf{(3-33)}$$

Where

- CTD_{ij} is the fraction (dimensionless) of radionuclide deposited directly onto plant surfaces found in the edible portion of pasture at harvest,

- T is the time (s) from accident to the end of growing season

- $CTCOEF_{ijn}$ is the crop transfer coefficient (amount transferred/amount deposited) (dimensionless),

- TE_j is the time (s) from the beginning of the year to the end of the growing season for crop j,

- TS_j is the time (s) from the beginning of the year to the beginning of the growing season for crop pasture,

- N is the number of terms in the crop retention model, as specified by the parameter NTTRM, and

- H_{ijn} is the total depletion rate of radionuclide i from surface of pasture due to weathering, grazing, and radioactive decay processes (s^{-1}).

and

$$H_{ijn} = \frac{ln(2)}{CTHALF_{ijn}} + \frac{ln(2)}{TE_j - TS_j} + \lambda_i, \tag{3-34}$$

Where

- $CTHALF_{ijn}$ is the half-life of weathering coefficient n (s), and
- λ_i is the decay constant for radionuclide i (s^{-1}).

Equation (3-33) is an illustrative example for cases of simple decay with no ingrowth, although MACCS also accounts for ingrowth as well. For pasture, the transfer of radioactive material deposited onto the surface of the growing crop is assumed to be limited to the period between the time of accident TI and the end of the growing season. If the accident occurs outside the growing season for pasture (i.e., $TI < TS$ or $TI > TE_j$), then $T = 0$ and no material is consumed via this pathway. If however, the accident occurs during the pasture growing season (i.e., $TS_j < TI < TE_j$), then the time T over which the transfer can occur is ($TE_j - TI$) and the direct deposition crop transfer factor for pasture in Equation (3-33) becomes

$$CTD_{ij} = \frac{1}{TE_j - TS_j} \cdot \sum_{n=1}^{N} \left(CTCOEF_{ijn} \cdot \frac{1 - e^{-H_{ijn} \cdot (TE_j - TI)}}{H_{ijn}} \right) \tag{3-35}$$

For all non-pasture crops, harvest is not a continuous process, and occurs at the end of the growing season. The transfer function consists of a weathering and radioactive decay term. The fraction of the deposited material found in the edible portion of the plant again depends on the amount of time between the time of the accident and the end of the growing season. Again, if TI < TS_j or $TI > TE_j$, then $CTD = 0$ for that radionuclide-crop pair. If $TS_j < TI < TE_j$, then

$$CTD_{ij} = \sum_{n=1}^{N} \left(CTCOEF_{ijn} \cdot e^{-L_{ijn} \cdot (TE_j - TI)} \right) \quad \textbf{(3-36)}$$

Where L_{ijn} is the total depletion rate for weathering and radioactive decay processes (s^{-1}), and

$$L_{ijn} = \frac{ln(2)}{CTHALF_{ijn}} + \lambda_i \quad \textbf{(3-37)}$$

where all variables are as previously defined.

Transfer of Radioactive Material Deposited onto Soil to Food Plants

Compared to direct deposition transfer processes, the transfer processes in which radioactive material is deposited onto the soil and subsequently taken up by plants are long-term mechanisms. Following deposition, the contaminants must be transferred to plants via root uptake and other soil uptake processes such as soil ingestion by grazing animals for this pathway to be effective. The user-supplied input variable TCROOT incorporates the overall transfer of the radionuclides by all these long-term uptake processes. Because a number of disparate processes are being combined, the transfer factor may be most readily derived empirically using current fallout data.

The transfer factor $TCROOT_{ij}$ is defined in the CHRONC user input file as a two-dimensional array. For each radionuclide-crop pair, it represents the fraction of the radioactive material deposited onto the soil being used to grow that crop which will eventually be consumed by humans. $TCROOT_{ij}$ is the sum of the following fractions: (1) the fraction of the material deposited onto the soil which will be incorporated into the edible portion of the crop via root uptake, CTR_{ij}, and (2) the fraction of the material deposited onto the soil which will be ingested directly by grazing animals, $TFSI_{ij}$. The only crop for which soil ingestion is a significant factor is pasture.

Transfer of Radioactive Material from Harvested Crops to Humans

Up to this point, we have described the phenomena that describe the fraction of the radioactive material deposited on farmland, which will be incorporated into edible portions of plants at the time of harvest or be consumed directly by food producing animals. This has been done for the two pathways: growing season and long-term uptake. What remains is to specify the efficiency of the transport mechanisms during the time period between the crop harvest and the consumption of the contaminated food by the population. These mechanisms include the direct consumption of the contaminated crop by the population as well as the population's consumption of contaminated animal products.

For each radionuclide-crop pair, a specific transfer factor is established for each pathway that describes the fraction of the radioactive material present in the crop at the time of harvest that will ultimately be consumed by humans. These transfer factors are defined for the direct consumption of the crop by the population and also for the consumption of animal products (milk and meat) produced by the animals fed the contaminated crops.

The transfer factors describing the fraction of radionuclide *i* present in the edible portion of crop *j* at harvest that would ultimately be ingested by the population for the growing season and long-term pathways are derived as follows:

$$\begin{aligned}
&\text{Crop-to-human} && CH_{ij} = DCYPCH_{ij} \cdot FPLSCH_{ij} \\
&\text{Crop-to-milk-to-human} && CMH_{ij} = DCYPCM_{ij} \cdot TFMLK_i \cdot DCYPMH_i \\
&\text{Crop-to-meat-to-human} && CBH_{ij} = DCYPCB_{ij} \cdot TFBF_i \cdot DCYPBH_i
\end{aligned} \tag{3-38}$$

All of these transfer factors on the right-hand side of Equation (3-38) are user-supplied input variables described in Table 3-2.

Overall Transfer of Radionuclides from Deposition to Ingestion

To establish overall transfer factors for the radionuclides deposited onto farmland following an accident, TF_{ij}, it is necessary to multiply the following factors: (1) those describing the transfer of material to the edible portion of the crop and (2) those describing the transfer of each radionuclide in the harvested crop-to-human via each possible route to humans.

For the growing season pathway, the overall transfer factors TF_{ij} for any radionuclide-crop pair (*i*,*j*) can be calculated as the product of an appropriate crop transfer factor (that is, CTD_{ij} or $TCROOT_{ij}$) and an appropriate transfer factor describing fraction of material in harvested crops ultimately eaten by human. That is, the overall transfer factors, TF_{ij}, for any radionuclide-crop pair (*i*,*j*) are as follows:

$$\begin{aligned}
&\text{Crop-to-human} && TF_{ij} = CTD_{ij} \cdot CH_{ij} \\
&\text{Crop-to-milk-to-human} && TF_{ij} = CTD_{ij} \cdot CMH_{ij} \\
&\text{Crop-to-meat-to-human} && TF_{ij} = CTD_{ij} \cdot CBH_{ij}
\end{aligned} \tag{3-39}$$

The analogous long-term soil-to-human uptake pathway overall transfer factors, TF_{ij}, are as follows:

$$\begin{aligned}
&\text{Crop-to-human} && TF_{ij} = TCROOT_{ij} \cdot CH_{ij} \\
&\text{Crop-to-milk-to-human} && TF_{ij} = TCROOT_{ij} \cdot CMH_{ij} \\
&\text{Crop-to-meat-to-human} && TF_{ij} = TCROOT_{ij} \cdot CBH_{ij}
\end{aligned} \tag{3-40}$$

With these transfer factors, MACCS can now compute the growing season pathway ingestion doses in Equations (3-31) and (3-32) and the long-term pathway ingestion dose in Equation (3-30).

3.4.4 Drinking Water Ingestion

When radioactive material is deposited onto the ground, some fraction of this material makes its way into drinking water that is consumed by people. To calculate ingestion doses, the user must give the model FDPATH a value of either “OLD” or “NEW.” Both models treat water ingestion the same. If the user specifies a value of “OFF,” MACCS does not calculate either food or drinking water ingestion doses.

The water ingestion dose calculated by MACCS is a population dose. The user must specify which radionuclides are to be included in the water ingestion pathway in the parameter NAMWPI. These radionuclides must be a subset of the radionuclides being considered in the food pathway.

The transport of deposited radionuclides into the drinking water supply begins when the early phase ends. Water bodies treated in MACCS as sources of drinking water are lakes, river systems, and estuaries, that is, fresh surface water bodies. The only liquid pathways that MACCS considers are those contained in the drinking water ingestion pathway. MACCS does not model other potential water pathways, such as farmland irrigation / sprinklers, water ingestion by livestock, or consumption of fish or other aquatic foods. As such, the liquid pathway modeling in MACCS is simple and intended to provide "scoping" estimates of the impact on doses and health effects.

MACCS models ingestion from the intake of drinking water as two separate paths: (1) drinking water doses from radionuclide deposition directly onto freshwater bodies and (2) drinking water doses from radionuclide deposition onto land with subsequent washoff into freshwater bodies. MACCS further splits this second path into two components, doses from initial washoff and doses from continuous long-term washoff.

The population dose from radionuclide *i* to organ *k* via the water ingestion pathway, DW_k (*person-Sv*), can therefore be defined by the following equation:

$$DW_k = DW_k^W + DW_k^L \tag{3-41}$$

Where

- DW_k is the population dose (*person-Sv*) from water ingestion to organ *k* from deposition in a spatial element,
- DW_k^W is the population dose (*person-Sv*) to organ *k* resulting from deposition onto fresh surface-water bodies of the spatial element, as defined below, and
- DW_k^L is the population dose (*person-Sv*) to organ *k* resulting from deposition onto land surfaces of the spatial element, also defined below.

The population ingestion dose from contamination depositing onto fresh surface-water bodies is the following:

$$DW_k^W = \left(\sum_i DCW_{ik} \cdot GC_i \cdot F_i^W\right) \cdot A \cdot FW \tag{3-42}$$

Where

- DW_k^W is the population water ingestion dose (*person-Sv*) resulting from the deposition of radionuclide *i* onto fresh surface-water bodies within a spatial element,
- DCW_{ik} is the ingestion dose coefficient (*person-Sv*/*Bq-ingested*), supplied by the DCF file,

- GC_i is the initial concentration of radionuclide i in a spatial element (Bq/m^2), calculated by Equation (3-7),

- F_i^W is the ingestion fraction (dimensionless) of radionuclide *i* from freshwater bodies, as specified either by the watershed data in the site data file or by the parameter $WINGF_i$,

- A is the area of the spatial element, as calculated by MACCS from the grid definitions, and

- FW is the freshwater fraction of the spatial element, as derived either from the site data file, or from the land fraction parameter (e.g., 1 – FRACLD).

The drinking water uptake fraction ($WINGF_i$) from freshwater bodies determines how much activity is eventually consumed by people. The models used to determine $WINGF_i$ can vary in complexity from the very simple (*e.g.*, a single uniformly mixed cell) to the very complex (e.g., three-dimensional fluid transport with temporal and spatial variability). Ideally, a value for $WINGF_i$ should be derived from a model for radionuclide transport through the surface-water system of the surrounding region.

With a site data file, the user can define up to four watersheds, each with a different drinking water uptake fraction ($WINGF_i$). For coastal sites, where both freshwater and ocean bodies need to be considered, the use of a site data file is necessary as it allows the analyst to define a separate ocean watershed where there is no anticipated drinking water uptake.

Of the activity deposited directly onto water and transferred initially from land to water, MACCS does not model decay and assumes that any reduction due to decay before consumption is negligible.

The ingestion dose from contamination depositing onto land is the following:

$$DW_k^L = \left(\sum_i DCW_{ik} \cdot GC_i \cdot F_i^L\right) \cdot A \cdot FL \tag{3-43}$$

- DW_k^L is the population water ingestion dose (*person-Sv*) resulting from the deposition of radionuclide *i* onto land of the spatial element,

- F_i^L is the transfer fraction (dimensionless) of radionuclide *i*, from land deposition to human ingestion, as defined below,

- FL is the land fraction of the spatial element (dimensionless), as specified by either the site data file or by the parameter FRACLD, and

- GC_i, DCW_{ik}, and A are defined the same as above.

MACCS assumes that of the activity that is initially deposited on land, some fraction makes its way through runoff into freshwater bodies. Therefore, the transfer fraction from land deposition to human ingestion F_i^L is simply the following:

$$F_i^L = F_i^{LW} \cdot F_i^W \tag{3-44}$$

Where F_i^W is the ingestion fraction from freshwater bodies (as defined before), and F_i^{LW} is the transfer fraction (dimensionless) of radionuclide *i*, from land deposition to freshwater supply.

As described by Helton, Muller, and Bayer (1985), MACCS models washoff from land to freshwater F_i^{LW} in two processes, (1) an initial washoff and (2) a constant fractional rate over time. As such, the transfer fraction F_i^{LW} from land deposition to the freshwater supply has two terms.

$$F_i^{LW} = FI_i + FS_i \tag{3-45}$$

Where

- FI_i is the fraction of initial washoff of radionuclide *i*, transferring from land to freshwater, as specified by WSHFRI, and

- FS_i is the fraction of slow washoff of radionuclide *i*, transferring from land to freshwater, defined below.

Of the initial washoff of land deposition FI_i, MACCS does not model decay and assumes that any reduction due to decay before potential consumption is negligible. The remaining material washes off into surface-water bodies at a constant rate and is subject to decay.

The drinking water pathway assumes that land is not a sink for material deposited on land containing the user-specified drinking water radionuclides. If it were not for radioactive decay, the model would eventually washoff all deposited material into water bodies. After the initial washoff, the fraction of material that eventually leaves due to slow washoff is given by the branching fraction between slow washoff and radioactive decay, as explained in the following development:

$$\frac{\lambda_{wi}}{\lambda_i + \lambda_{wi}} \tag{3-46}$$

This can be shown analytically by letting $x_i(t)$ represent the amount of available radionuclide *i* on land surfaces at time *t* (*s*):

$$\frac{dx_i}{dt} = -(\lambda_i + \lambda_{wi}) \cdot x_i \tag{3-47}$$

with the initial condition

$$x_i(t = 0) = (1 - FI_i) \cdot x_{0i} \tag{3-48}$$

Where

- $x_i(t)$ is the amount (*Bq*) from radionuclide *i* on the land surfaces at time *t* after the initial washoff,

- λ_i is the radioactive decay constant for radionuclide i (s^{-1}),

- λ_{wi} is the washoff rate (s^{-1}) of radionuclide *i* from land to a freshwater system, specified by parameter WSHRTA$_i$,

- FI_i is the fraction of initial washoff of radionuclide *i*, transferring from land to freshwater, as specified by WSHFRI$_i$, and

- x_{0i} is the initial amount of activity (*Bq*) from radionuclide *i* that was deposited onto land surfaces following the accident, which can be given by $GC_i \cdot FL$.

Integration of Equation (3-47) gives the following expression for $x_i(t)$:

$$x_i(t) = (1 - FI_i) \cdot x_{0i} \cdot e^{-(\lambda_i + \lambda_{wi})t} \tag{3-49}$$

Then, the total amount of radionuclide *i* that is slowly washed off land surfaces WS_i (*Bq*) between from *t* = 0 to *t* = ∞ is the following:

$$\begin{aligned} WS_i &= -\lambda_{wi} \int_0^\infty x_i(t)dt \\ &= -(1 - FI_i) \cdot x_{oi} \cdot \lambda_{wi} \int_0^\infty e^{-(\lambda_i + \lambda_{wi})t}\, dt \\ &= (1 - FI_i) \cdot x_{0i} \cdot \frac{\lambda_{wi}}{\lambda_i + \lambda_{wi}} \end{aligned} \tag{3-50}$$

Equation (3-50) is an illustrative example for cases of simple decay with no ingrowth, although MACCS also accounts for ingrowth as well.

From this, the faction of slow washoff FS_i (dimensionless) is simply the following:

$$FS_i = \frac{WS_i}{x_{oi}} = (1 - FI_i) \cdot \frac{\lambda_{wi}}{\lambda_i + \lambda_{wi}} \tag{3-51}$$

Finally, by substituting Equation (3-51) into Equation (3-45), and then substituting this into Equation (3-44), the transfer fraction F_i^L of radionuclide *i* from land deposition to human ingestion is the following:

$$F_i^L = \left[FI_i + (1 - FI_i) \cdot \frac{\lambda_{wi}}{\lambda_i + \lambda_{wi}}\right] \cdot F_i^W \tag{3-52}$$

Where

- FI_i is the fraction of initial washoff (dimensionless) of radionuclide i, transferring from land to freshwater, as specified by the parameter WSHFRI$_i$, and

- λ_i is the radioactive decay constant (s^{-1}) for radionuclide i,

- λ_{wi} is the washoff rate (s^{-1}) of radionuclide i from land to a freshwater system, specified by the parameter WSHRTA$_i$

- F_i^W is the ingestion fraction (dimensionless) of radionuclide i from freshwater bodies, as specified either by the watershed data in the site data file or by the parameter WINGF$_i$,

Finally, after substituting Equation (3-44) into Equation (3-43), the drinking water ingestion dose from land contamination can be determined.

3.4.5 Decontamination Workers

Decontamination workers engaged in the cleanup effort of properties receive groundshine doses. These doses do not contribute to the individual consequence metrics, but like ingestion doses, they do contribute to collective consequence metrics in the spatial element where deposition occurs. MACCS assumes that decontamination occurs at the beginning of the long-term phase, and therefore worker doses also begin at this time and continue for a duration of $TIMDEC_\ell$. If there is no decontamination in the spatial element, there is no decontamination worker dose.

Since the decontamination workers are assumed to wear respirators, their inhalation doses are not calculated in MACCS. These worker doses in a spatial element are calculated for the duration of decontamination ($TIMDEC_\ell$). The decontamination worker dose to organ k is divided into two groups, non-farm and farm decontamination:

$$DWD_k = DWD_k^{NF} + DWD_k^F \tag{3-53}$$

The calculation of decontamination worker doses is like the late groundshine dose in Equation (3-19), except that worker doses are multiplied by the number of workers to give a worker population dose. The decontamination worker population dose in non-farm areas is as follows:

$$DWD_k^{NF} = \left(\sum_i DRCG_{ik} \cdot GC_i \cdot IEF_i\right) \cdot NFWorkers_\ell \tag{3-54}$$

Where

- DWD_k^{NF} is the worker population dose (*person-Sv*) to organ k for performing non-farm decontamination in a spatial element,

- $DRCG_{ik}$ is the groundshine dose rate coefficient (*Sv-m*^{2}*/Bq-s*) to the organ k for the radionuclide i, supplied in the DCF file,

- GC_i is the ground concentration (*Bq/m²*) of radionuclide i in the spatial element, calculated by Equation (3-7),

- IEF_i is the integrated exposure factor (*s*) for radionuclide i, discussed below, and

- $NFWorkers_\ell$ is the number of non-farm decontamination workers (*persons*) required to perform level ℓ decontamination, defined below.

The integrated exposure factor IEF_i is essentially the same as shown in Equation (3-20). However, integration period for decontamination workers begins at the start of decontamination (i.e., the long-term phase) and ends after a period of $TIMDEC_\ell$. MACCS does not consider a reduction in the worker doses due to their decontamination efforts. This dose reduction is only applied after decontamination is complete.

The number of non-farm decontamination workers is calculated using the following equation:

$$NFWorkers_\ell = \frac{NFCost_\ell \cdot Pop \cdot NFLaborFrac_\ell}{(LaborCost \cdot t_\ell)} \tag{3-55}$$

Where

- $NFCost_\ell$ is the level ℓ decontamination cost (*$/person*) of non-farm property in a spatial element, as specified by the parameter CDNFRM_ℓ,

- Pop is the number of persons in a given spatial element (*persons*), as defined by either the site data file or calculated by the population density (POPDEN) and the size of the spatial element (from the grid definitions),

- $NFLaborFrac_\ell$ is the fraction of non-farm level ℓ decontamination cost that is from labor (dimensionless), as specified by the parameter FRNFDL_ℓ,

- $LaborCost$ is the labor cost (*$/worker-yr*), as specified by the parameter DLBCST_ℓ, and

- t_ℓ is the work time (*s*) required to perform level ℓ decontamination, which is the decontamination period (TIMDEC_ℓ) multiplied by the fraction of the decontamination period (TFWKNF_ℓ) that non-farm decontamination workers spend in the contaminated area.

The decontamination worker population dose in farm areas is as follows:

$$DWD_k^F = \left(\sum_i DRCG_{ik} \cdot GC_i \cdot IEF_i\right) \cdot FWorkers_\ell \tag{3-56}$$

Where

- DWD_k^F is the worker population dose (*person-Sv*) to organ k for performing farm decontamination in a spatial element,
- $FWorkers_\ell$ is the number of farm decontamination workers (*persons*) required to perform level ℓ decontamination, defined below, and
- $DRCG_{ik}$, GC_i, and IEF_i are the same as in Equation (3-54).

The number of farm decontamination workers is calculated using the following equation:

$$FWorkers_\ell = \frac{FCost_\ell \cdot FarmArea \cdot FLaborFrac_\ell}{(LaborCost \cdot t_\ell)} \tag{3-57}$$

Where

- $FCost_\ell$ is the level ℓ decontamination cost (*$/hectare*) of farm property in a spatial element, as specified by the parameter $CDFRM_\ell$,
- $FarmArea$ is the farm area (*hectares*) in a given spatial element, given by the size of the spatial element (as specified by the grid definitions) multiplied by the farm fraction (as derived either from the site data file, or from the land fraction [FRACLD] and farm fraction parameters [FRCFRM]).
- $FLaborFrac_\ell$ is the fraction of farm level ℓ decontamination cost that is from labor (dimensionless), as specified by the parameter $FRFDL_\ell$,
- $LaborCost$ is the labor cost (*$/worker-yr*), as specified by the parameter $DLBCST_\ell$, and
- t_ℓ is the work time (*s*) required to perform level ℓ decontamination, which is the decontamination period ($TIMDEC_\ell$) multiplied by the fraction of the decontamination period ($TFWKF_\ell$) that farm decontamination workers spend in the contaminated area.

3.5 Dosimetry Model Outputs

MACCS reports nine output categories related to the dosimetry model. Early dose outputs are exposures from the early phase (generated by the EARLY module) and late dose outputs are exposures from the intermediate and long-term phase (generated by the CHRONC module). Total dose from both early and late exposures require both the EARLY and CHRONC modules. Table 3-3 gives a breakdown of each output category:

Table 3-3 Dosimetry Output Category Breakdown by Module

Result Type	EARLY	CHRONC	Cohort-specific Results	Method of Combining Cohorts
Type 3: Population Exceeding Dose Threshold	X		Yes	Sum
Type 5: Population Dose	X	X	Yes	Sum
Type 6: Centerline Dose	X	X	Yes	Weighted average
Type A: Peak Dose for Specified Distances	X	X	Yes	Weighted average
Type B: Peak Dose for Specified Spatial Elements	X	X	Yes	Weighted average
Type C: Land Area Exceeding Dose	X		Yes	N/A
Type C Flag: Dose by Grid Element	X	X	Yes	Weighted average
Type D: Land Area Exceeding Concentration	X		No	N/A
Type D Flag: Ground Concentration by Grid Element	X		No	N/A
Type 9: Breakdown of Late Population Dose		X	No	N/A
Type 13: Maximum Annual Food Ingestion Dose		X	No	N/A

Type D results ("Land Area Exceeding Concentration") are based on concentration rather than dose; however, they are still included in this section as they are part of the EARLY module. This is because the Type D results, like most of the dosimetry-related outputs, use the off-centerline correction factors discussed in Section 3.2.

When an output comes from both the EARLY module and the CHRONC module (i.e., Type 5, 6, A, B, and C flag), the overall results from the two modules are summed together. If the CHRONC module is not run, MACCS only reports the early phase contribution in the overall results. This would be an incomplete value if the intermediate or long-term phase is relevant to the analysis.

Many of the individual dose outputs (i.e., Type 6, A, B, and C flag) do not include the indirect pathways from food or water ingestion doses or decontamination worker doses. Because of additional transport of food and water, ingestion doses do not necessarily occur in the spatial element where deposition occurs, and MACCS does not attempt to model the actual location. Thus, the reported values of individual doses and associated individual cancer risk are based on a partial set of dose contributions. Decontamination workers are likely to be a different cohort than residents and thus these doses are not attributed to these dose outputs either.

The Type 5 ("Population Dose") output includes both the direct and indirect pathways when CHRONC is run, making this output the most complete of all dose output types. Even though the recipients of the indirect doses may not live in this location, the Type 5 output attributes ingestion and decontamination worker doses to the spatial element where deposition occurred.

Except for Type D results, the outputs produced by the EARLY module are cohort specific. The overall early results are a combination of the cohort results. Type 6, A, B, and C flag outputs are individual doses. Therefore, the overall early results from these outputs are a weighted average based on the population fraction of the cohort. MACCS does not report overall early results for Type C. The remaining two types of early results (i.e., Type 3 and 5) combine the early cohorts using simple summations. The mathematical expressions for calculating the overall results depend on the cohort model selected by the user and is discussed in Section 1.5.

Type 3: Population Exceeding Early Dose Threshold

The Type 3 output provides the number of people in the spatial grid who receive acute or lifetime dose to a user-specified organ from exposures in the early phase that exceeds a user-specified dose threshold. The Type 3 output only considers early doses generated by the EARLY module, and there is no analogous capability for late doses generated by the CHRONC module.

The early dose D_{in}^{E} (*Sv*) to a given organ from an individual in cohort *i* and spatial element *n* is shown in Equation (3-8). MACCS examines the early dose D_{in}^{E} for each cohort and spatial element and compares this value to the user-specified dose threshold. When early dose D_{in}^{E} exceeds the given dose threshold, those individuals are counted in the tally of the population in the Type 3 output. Protective actions can limit the early D_{in}^{E} dose, which in turn can limit the population that exceeds the user-specified dose threshold.

Type 5 Results: Population Dose

The population dose (*person-Sv*) is the lifetime dose to a user-specified organ in the population of a given cohort and a region of interest. The user defines the region of interest by specifying the two radial intervals that define the range of the region. The Type 5 output considers early doses generated by the EARLY module as well as late doses generated by the CHRONC module when the CHRONC module is run. This includes ingestion and decontamination worker doses.

Population dose is a collective metric to represent the public as opposed to an individual. When CHRONC is run, this output includes doses from all pathways, including the indirect pathways. The indirect pathways are population doses that are not tallied in individual resident doses, these being (1) food and water ingestion doses resulting from material deposited in the region and (2) doses to decontamination workers working in the region. When CHRONC is not run, MACCS only reports the early phase contribution to the population dose.

Since there are no indirect pathways in the early phase, the early population dose is simply the early individual dose multiplied by the population. The early population dose $D_{i}^{E,POP}$ (*person-Sv*) to a given organ in individuals of a given region and within cohort *i* is the following:

$$D_{i}^{E,POP} = \sum_{n} D_{in}^{E,POP} = \sum_{n} D_{in}^{E} \cdot POP_{in} \quad \textbf{(3-58)}$$

Where

- $D_{in}^{E,POP}$ is the early population dose (*person-Sv*) to a given organ in the population of cohort *i* and spatial element *n*,

- D_{in}^{E} is the early dose (*Sv*) to a given organ from an individual in cohort *i* and spatial element *n*, as shown in Equation (3-8),

- POP_{in} is the population of cohort *i* in spatial element *n*, and

- n is a spatial element within the user-specified region.

The early dose D_{in}^{E} to a given organ is the sum from all early pathways except skin deposition. The population POP_{in} depends on the cohort weighting method WTNAME. See Section 1.3.

The late population dose $D^{L,POP}$ (*person-Sv*) to a given organ from deposition in a given region is the following:

$$D^{L,POP} = \sum_{n} D_{n}^{L,POP} = \sum_{n} (D_{n}^{L} \cdot POP_{n} + DF_{n} + DW_{n} + DWD_{n}) \tag{3-59}$$

Where

- $D_{n}^{L,POP}$ is the late population dose (*person-Sv*) to a given organ from deposition in spatial element *n* during the intermediate and long-term phase,

- D_{n}^{L} is the late dose (*Sv*) to a given organ from deposition in spatial element *n*, as shown in Equation (3-17),

- POP_{n} is the population in spatial element *n*,

- DF_{n} is the population dose (*person-Sv*) to a given organ via food ingestion from the deposition onto the farmland area of spatial element *n*, given by Equation (3-24) when using COMIDA2 or Equation (3-29) when using the original food-chain model,

- DW_{n} is the population dose (*person-Sv*) to a given organ via water ingestion from deposition in spatial element *n*, as shown Equation (3-41),

- DWD_{n} is the worker population dose (*person-Sv*) to a given organ for performing decontamination in spatial element *n*, as shown in Equation (3-53), and

The population dose $D_{n}^{L,POP}$ includes the direct pathways, which are the groundshine and inhalation resuspension pathways included in the late individual dose D_{n}^{L}, and the indirect pathways, those being food ingestion, water ingestion, and decontamination worker doses.

Finally, the overall population dose D^{POP} (*person-Sv*) to a given organ from a given region is the early and late population doses summed together:

$$D^{POP} = D^{E,POP} + D^{L,POP} \quad \textbf{(3-60)}$$

Type 6 Results: Centerline Dose

Centerline dose is the dose (*Sv*) from a user-specified dose pathway to a user-specified organ in a phantom individual directly under the plume path. The Type 6 output reports the centerline dose for each radial interval within a region of interest. The user defines the region of interest by specifying the two radial intervals that define the range of the region. The Type 6 output considers early doses generated by the EARLY module as well as late doses generated by the CHRONC module when the CHRONC module is run. Type 6 output does not include ingestion and decontamination worker doses. Result are only available when wind shift is turned off (i.e., IPLUME = 1). The centerline dose is not affected by protective actions.

The dose calculations in Sections 3.3 and 3.4 use an off-centerline correction factor to adjust the centerline dose to an average dose for the spatial element. In order to calculate centerline dose, these off-centerline correction factors are not included. Note that acute and lifetime inhalation doses from the early phase require different dose coefficients. The centerline dose results may be obtained for the pathways described in Table 3-4.

Table 3-4 Centerline Dose Pathway Options and Derivation

Pathway	Description	Derivation[a]
CLD	Cloudshine dose	Equation (3-9)
GRD	Groundshine dose	Equation (3-10) + Equation (3-19)
INH ACU	Acute dose from inhalation of the passing plume	Equation (3-12), using acute dose coefficients
INH LIF	Lifetime dose from inhalation of the passing plume	Equation (3-12), using lifetime dose coefficients
TOT ACU	Total acute dose from all direct exposure pathways	Equation (3-8), using acute dose coefficients
TOT LIF	Total lifetime dose from all direct exposure pathways	Equation (3-8) + Equation (3-17), using lifetime dose coefficients
RES ACU	Acute dose from inhalation of resuspended material after plume passage	Equation (3-13), using acute dose coefficients
RES LIF	Lifetime dose from inhalation of resuspended material after plume passage	Equation (3-13) + Equation (3-22), using lifetime dose coefficients

[a] These equations include an off-centerline correction factor. These must be excluded to be obtain the centerline dose.

Type A Results: Peak Dose for Specified Distances

The peak dose for a Type A output is the maximum dose (*Sv*) to a user-specified organ from a spatial element in a radial interval. The Type A output reports a maximum dose for each radial interval with a region of interest. The user defines the region of interest by specifying the two radial intervals that define the range of the region. The Type A output considers early doses generated by the EARLY module as well as late doses generated by the CHRONC module when the CHRONC module is run. Type A output does not include ingestion and decontamination worker doses.

The Type A output first evaluates the dose of each spatial element in a radial interval considering all plume segments and then reports the maximum dose from this set of spatial elements. When a Type A output is requested, MACCS reports the peak dose for each radial interval within the specified range. For each radial interval, the peak dose can be in a different direction. The peak dose is an individual type output metric, representing a dose to an individual instead of a population.

For early doses, the peak dose is from a fine spatial element. For late doses, the peak dose is a dose from a coarse spatial element since the fine spatial elements are not analyzed. MACCS calculates the dose of each spatial element in a radial interval in the same manner as previously discussed. The early dose D_{in}^{E} (*Sv*) to a given organ from an individual in cohort *i* and spatial element *n* is derived using Equation (3-8). The late dose D_{n}^{L} (*Sv*) to a given organ from deposition in spatial element *n* is derived using Equation (3-17). Note that early doses from a spatial element depend on the definition of that cohort in terms of evacuation and relocation. While the population of a grid element may receive a dose outside their original spatial element during evacuation, all doses that population receives are assigned to the spatial element that the population originates from. Therefore, peak doses do not necessarily represent stationary positions on the spatial grid.

The overall results represent the combination of early cohort doses when EARLY is run, and a combination of both early and late doses when both EARLY and CHRONC are run. However, the overall results may be misleading because peak doses for the various cohorts may occur at different angular locations. Combining these values may be questionable when multiple plume segments travel in different directions (i.e., when NUMREL is greater than 1 and IPLUME is 2 or 3).

Peak doses are similar to centerline doses; however, a centerline dose is not available when wind shift is considered (i.e., IPLUME = 2 or 3), as this may cause two or more plume segments to travel in different directions and no single centerline may exist. The implementation of the peak dose result differs from centerline dose in two ways: (1) there is no option to report a breakdown of individual doses by pathway and (2) the peak dose, whether it be an early dose from a fine spatial element or a late dose from a coarse spatial element, represents an average dose over the width of a spatial element and is not a centerline value. In other words, the peak dose includes the off-centerline correction factor that adjusts the centerline dose to an average dose for the spatial element and considers the contribution from all plume segments.

Type B Results: Peak Dose for Specified Spatial Elements

The Type B result provides the maximum dose (*Sv*) to a user-specified organ from a fine spatial element in a user-specified radial interval and angular direction (*r*, *θ*). The radial interval and angular direction specify a (coarse) spatial element. The Type B output considers early doses generated by the EARLY module as well as late doses generated by the CHRONC module when the CHRONC module is run. Type B output does not include ingestion and decontamination worker doses.

Like the peak dose in the Type A results, the peak dose in the Type B results is a maximum dose from a set of spatial elements considering the contribution from all plume segments. Unlike the Type A results, the Type B results are for a specific angular direction. Therefore, the Type B output is the peak dose for a specified (coarse) spatial element, whereas the Type A output is the peak dose for a specified radial interval.

For the early phase, the peak dose of the Type B output is the maximum dose of the handful of fine spatial elements within the coarse spatial element. For the late doses, the peak dose is simply the dose in the coarse spatial element.

The peak dose is an individual type output metric, representing a dose to an individual instead of a population. As before, the early dose D_{in}^{E} (*Sv*) to a given organ from an individual in cohort *i* and spatial element *n* is derived using Equation (3-8). The late dose D_{n}^{L} (*Sv*) to a given organ from deposition in spatial element *n* is derived using Equation (3-17). The overall results represent the combination of early doses when only EARLY is run and a combination of both early and late doses when both EARLY and CHRONC are run.

Note that while the peak dose of the early phase cohorts may represent slightly different locations within the coarse spatial element, they are combined regardless according to the cohort modeling option chosen by the user. Still, these doses are likely more meaningful than the overall results of the Type A output, which may combine cohorts of completely different angular directions.

The location of the spatial element depends on the radial index (which can range from 1 to NUMRAD) and an angular index (which can range from 1 to NUMCOR). Following the convention used in other parts of the code, an angular index of 1 "points" to an individual assumed to be located north of the release point, with successive directions rotating clockwise around the compass. When using 16 compass directions, an angular index of 16 points to the NNW direction.

Type C Results: Land Area Exceeding Dose

The main output of the Type C output category is the land area (*hectares*) that exceeds a user-specified dose level to a user-specified organ during the early phase.

When early phase exposures to an individual of a cohort would exceed the given dose level, the land area from that spatial element is counted in the tally of land area in the Type C output. As before, the early dose D_{in}^{E} (*Sv*) to a given organ from an individual in cohort *i* and spatial element *n* is derived using Equation (3-8). Because results are specific to a cohort, protective actions affect this result. Unlike the other output categories, MACCS does not report an overall land area exceeding dose based on an average for the different cohorts. MACCS also does not report the land area exceeding ambient doses, although a user can determine this by running a calculation that does not allow protective actions to occur in a given cohort.

Type C Flag Results: Dose by Grid Element

The Type C flag output provides the dose (Sv) to a user-specified organ for all spatial elements. The Type C output considers early doses generated by the EARLY module as well as late doses generated by the CHRONC module when the CHRONC module is run. Type C output does not include ingestion and decontamination worker doses. Users can display the dose value in every spatial element by setting the flag in the Type C output to “TRUE.” Unlike the regular Type C output, the Type C flag reports an overall result based on an average for the different cohorts.

For wide plumes, the Type A output is equal to or slightly greater than the largest Type C flag result in the radial interval. This is because Type A results are peak results from a fine spatial element, whereas the Type C flag results are from coarse spatial elements.

Type D Results: Land Area Exceeding Concentration

The main output of the Type D output category provides the land area (*hectares*) that exceeds a user-specified ground concentration for a specified radionuclide within a user-specified distance.

When a radionuclide ground concentration (*Bq/m²*) at the end of the early phase exceeds user-specified ground concentration (*Bq/m²*), the land area from that spatial element is counted in the tally of land area in the Type C output. MACCS limits the tally to the region within the outer radius of a user-specified radial interval. The ground concentration GC_i of radionuclide i in a spatial element as a result of dry and wet deposition from all plume segments is derived in Equation (3-7). This considers the off-centerline correction factor and is adjusted for radioactive decay and ingrowth for the period between the start of the accident and the end of the early phase.

Type D Flag Results: Ground Concentration by Grid Element

The Type D flag output provides the ground concentrations (*Bq/m²*) and the time-integrated ground-level air concentrations (*Bq-s/m³*) for all spatial elements and for a user-specified radionuclide. Users can display the dose value in every spatial element by setting the flag in the Type D output to "TRUE."

The time-integrated ground-level air concentration χ_i^G (*Bq-s/m³*) of radionuclide i is based on Equation (2-58), and then it is adjusted by decay and ingrowth, multiplied by the off-centerline correction factor, and summed for all plume segments.

The ground concentration GC_i (*Bq/m²*) of radionuclide i at the end of the early phase is derived in Equation (3-7). This considers a sum for ground concentrations from all plume segments, adjusted by decay and ingrowth, and is multiplied by the off-centerline correction factor.

Type 9 Results: Breakdown of Late Population Dose

The Type 9 output provides a breakdown of late population dose (*person-Sv*) to an organ for a region of interest for different pathways. For groundshine and resuspension inhalation, the dose is received by the resident population from within the region of interest. For ingestion and doses to decontamination workers, the dose is from contamination in the region of interest but could be received by individuals who reside elsewhere.

The output produces a block of either 12 or 17 dose results depending on which food-chain model is being used, as identified below. When FDPATH is set to "OFF," all ingestion doses (including water ingestion) display a value of zero. All the dose results are reported in *person-Sv* by default, although the units are listed simply as Sieverts (*Sv*) in the output file. The following dose results are reported:

Table 3-5 Breakdown of late population dose outputs without food-chain model

Output Name	Description	Derivation
TOTAL LONG-TERM PATHWAYS DOSE	The total late population dose from groundshine and resuspension, from the consumption of contaminated food, from the ingestion of contaminated surface water, and from decontamination work.	Equation (3-18)
LONG-TERM DIRECT EXPOSURE PATHWAYS	The late population dose to resident population from groundshine and inhalation of resuspended aerosols.	Equation (3-17), multiplied by the population of individual residents for each spatial element in the region of interest
TOTAL INGESTION PATHWAYS DOSE	The total late population dose from the consumption of contaminated dairy products, contaminated non-dairy products, and contaminated water.	Equation (3-41), plus either Equation (3-24) when using the COMIDA2 model or Equation (3-29) when using the original food-chain model
LONG-TERM GROUNDSHINE DOSE	The late population dose received by resident population from groundshine.	Equation (3-19)
LONG-TERM RESUSPENSION DOSE	The late population dose received by resident population from inhalation of resuspended aerosols.	Equation (3-22)
POP-DEPENDENT DECONTAMINATION DOSE	The population dose received by workers from groundshine when they are performing "population dependent" (non-farm) decontamination (decontamination workers receive no inhalation dose).	Equation (3-54)
FARM-DEPENDENT DECONTAMINATION DOSE	The population dose received by workers from groundshine when they are performing farm-dependent (farmland) decontamination (decontamination workers receive no inhalation dose).	Equation (3-56)
WATER INGESTION DOSE	The late population dose from ingestion of contaminated surface water.	Equation (3-41)

When the original MACCS food-chain model is used (FDPATH = “OLD”), the following food pathway results are reported:

Table 3-6 Breakdown of ingestion dose outputs from original food-chain model

Output Name	Description	Derivation
MILK GROWING SEASON DOSE	The population dose resulting from consumption of milk and dairy products contaminated because of deposition onto crops during the growing season.	Equation (3-31)
CROP GROWING SEASON DOSE	The population dose resulting from consumption of non-milk food products contaminated because of deposition onto crops during the growing season.	Equation (3-32)
MILK LONG-TERM DOSE	The population dose resulting from consumption of milk and dairy products contaminated by long-term uptake of crops.	Equation (3-30), using farmland and transfer fractions for milk
CROP LONG-TERM DOSE	The population dose resulting from consumption of non-milk food products contaminated by long term uptake of crops.	Equation (3-30), using farmland and transfer fractions for non-milk products

When the COMIDA2 food-chain model is used (FDPATH = “NEW”), the following food pathway results are reported. Each of these individual outputs is derived using the formula in Equation (3-24) although for the specific crops of interest:

Table 3-7 Breakdown of ingestion dose outputs from COMIDA2 food-chain model

Output Name	Description
INGESTION OF GRAINS	The population dose resulting from consumption of grains by humans.
INGESTION OF LEAF VEG	The population dose resulting from consumption of leafy vegetables by humans.
INGESTION OF ROOT CROPS	The population dose resulting from consumption of root crops by humans.
INGESTION OF FRUITS	The population dose resulting from consumption of fruits by humans.
INGESTION OF LEGUMES	The population dose resulting from consumption of legumes by humans.
INGESTION OF BEEF	The population dose resulting from consumption of beef by humans.
INGESTION OF MILK	The population dose resulting from consumption of milk by humans.
INGESTION OF POULTRY	The population dose resulting from consumption of poultry by humans.
INGESTION OF OTHER MEAT CROPS	The population dose resulting from consumption of other animal products by humans.

Type 13 Results: Maximum Annual Food Ingestion Dose

The Type 13 output is the maximum annual food ingestion dose (Sv) within a user-specified region of interest for effective dose or thyroid dose to an individual, with the first-year dose beginning at the end of the early phase. No other organs are available for this result and this output category is only available when using the COMIDA2 food-chain model.

The annual dose DF_{jk} from food ingestion exposures to an individual in year j to organ k through all crop pathways resulting from the deposition onto farmland of the spatial element is derived in Equation (3-26). This is the same derivation MACCS uses to determine long-term farmland restrictions in years 2 through 9 by comparison against the farmability criterion DOSELONG.

For the Type 13 output, MACCS examines the annual food ingestion doses in years 1 through 9 for each spatial element, and displays the maximum value found in each radial interval in the output. MACCS assumes the food ingestion dose in spatial elements with no farmland is zero, and that the food ingestion dose during farmland interdiction is zero.

4 PROTECTIVE ACTIONS

Protective actions are measures designed to reduce radiation exposures and can have a significant impact on accident consequences. They can affect when individuals occupy or leave an area, the amount of contamination in an area, or when food or land is interdicted. Because they restrict public doses, the protective actions considered in MACCS are inputs to the dose equations in Section 3; however, protective actions are also a major source of economic costs and other impacts discussed in Section 5. Thus, they bridge the two topics. The user should realize that choices on modeling protective actions affect estimated doses, resulting health effects, and economic losses. Deciding to model protective actions in a minimal way because economic losses are not important for an application can significantly affect other results.

The protective actions that MACCS considers include sheltering, evacuation / early relocation, potassium iodide (KI) ingestion, decontamination, habitation restrictions, and farming restrictions. Some protective actions such as evacuation, habitation restrictions, and farming restrictions either reduce the exposure period or prevent exposure from occurring at all. Reducing the exposure period normally also reduces the initial exposure intensity. Other protective actions such as sheltering, KI ingestion, and decontamination directly reduce the exposure intensity.

MACCS divides the accident and associated protective actions into three phases: early phase, intermediate phase, and long-term phase.

The early phase is the period during and immediately following the accident. In MACCS, it is a user specified period (ENDEMP) that begins after accident initiation. Evacuation, sheltering, and KI ingestion are protective actions that the public may take during the early phase. These protective actions are generally called the emergency response and are directed by offsite response organizations. Defining protocols for emergency response protective actions is the basis for radiological emergency preparedness programs in the United States.

In the early phase, the decision to enact emergency protective actions may be based either on conditions at the nuclear site or on offsite measurements. Consistent with this, MACCS has two separate emergency response models: (1) the evacuation and sheltering model, and (2) early relocation model. Even though radiological emergency plans consider early relocation (as modeled in MACCS) to be evacuation, the term “evacuation” in MACCS refers specifically to actions in the evacuation and sheltering model. There is also an early protective action model for potassium iodide ingestion to protect the thyroid. The emergency response models are described in Section 4.2.

After the early phase, the intermediate phase begins, which is a period that radiological emergency plans in the U.S. may or may not address. In MACCS, the user determines the length of the intermediate phase with the parameter DUR_INTPHAS. The intermediate phase duration can be as long as 30 years, or the user can choose not to use an intermediate phase by giving DUR_INTPHAS a value of 0. During this phase, MACCS considers only relocation (i.e., habitability restrictions). MACCS implements this action if the projected dose during the intermediate phase exceeds some dose limit specified by the user. Section 4.3 discusses the intermediate phase protective actions in more detail.

The long-term phase begins after the intermediate phase and is intended to represent the remaining duration of consequences, as discussed in Section 4.4. Radiological emergency plans do not address the long-term phase, and federal guidance (EPA, 2017) states that many long-term protective actions and recovery policies are expected to be determined post-accident. This makes simulating a long-term phase uncertain, as recovery from an actual nuclear accident may proceed differently than envisioned by the long-term protective action models in MACCS. Nevertheless, long-term protective actions may have the most impact on the overall consequences of a nuclear accident. Long-term protective actions in MACCS include decontamination, temporary and permanent relocation (i.e., habitation restrictions), and farming restrictions. In MACCS, the purpose of decontamination and habitation restrictions is to control the late radiation exposure from groundshine and resuspension inhalation. The purpose of farming restrictions is to control doses from ingestion of food produced on contaminated farmland. MACCS does not model reentry before habitation restrictions are lifted. MACCS assumes that areas with permanent restrictions are condemned and that farmland that exceeds habitation restrictions is not farmable, regardless of farmability criteria. MACCS evaluates the farm restrictions at discrete annual periods and habitation restrictions continuously. As such, non-farm areas can be interdicted for partial years, whereas farm areas are interdicted for whole number of years.

In MACCS, the protective actions in the three phases are largely independent of each other. Therefore, any evacuation orders from the early phase are immediately lifted at the end of the phase, and MACCS assumes people immediately return unless prevented by intermediate phase habitation restrictions. At the end of the intermediate phase, intermediate habitability restrictions are immediately lifted, and MACCS assumes people immediately return unless prevented by long-term habitation restrictions. And, when doses no longer exceed the long-term habitability criterion,

MACCS assumes the habitation restrictions are lifted and that the population immediately and fully returns. Note that realistically, reoccupancy may have its own set of return criteria and timeline that are not determined until after the accident, and it is unlikely everyone would return.

Many protective action decisions are based on a projected dose an individual would receive with no protection. If a projected dose exceeds a dose criterion to the critical organ during a specified exposure period, it triggers a protective action. Dose projections are used for the early, intermediate, and long-term phase. When performing dose projections, MACCS uses protection factors assuming normal activity. However, certain portions of the population (e.g., outdoor workers) tend to have much less shielding than an average individual. To conservatively ensure that everyone is protected, protective action guides commonly use simplifying assumptions regarding shielding, such as assuming people are unprotected. Users should recognize that because of this, actual decisions for protective actions may be more extensive than what MACCS predicts.

Another characteristic to recognize is that MACCS models relocation decisions in the intermediate and long-term phases based on a single dose criterion, not multiple criteria. In contrast, EPA guidance recommends that relocation should be based on two projected doses, specifically the exceedance of an anticipated effective dose of 2 rem in the first year after the accident and 0.5 rem in the second year. The interpretation is that these dual criteria should be used together to make a single decision on relocation. Additionally, some countries enact protective actions based on dose rate rather than projected dose. MACCS does not allow the user to base actions on dose rates.

Another important characteristic worth noting is that MACCS does not have the ability to model decontamination in lightly contaminated areas that remain inhabited. MACCS uses the same dose criterion for relocation and decontamination, thereby assuming that decontamination is limited to habitation restricted areas. While much of the decontamination policy in the U.S. is expected to be determined post-accident, users should recognize that decontamination may occur in both habitation restricted and unrestricted areas. For instance, after the Fukushima accident, Japan had a restricted area roughly based on 20 mSv/yr, and a final cleanup level of 1 mSv/yr that includes many areas both inside and outside the restricted area. Likewise, Chernobyl also had cleanup outside restricted areas. In the US, public exposure limits of 1 mSv/yr (100 mrem/yr; 10 CFR 20) are below the EPA relocation of 20 mSv (2 rem) in the first year and 5 mSv (0.5 rem) in the second year. Cleanup levels of U.S. sites contaminated (not caused by nuclear power plant accidents) vary but are typically more strict than public exposure limits (Interstate Technology and Regulatory Council [ITRC], 2002), and U.S. operational guidelines for cleanup after a radionuclide dispersal device generally indicates a range 0.04 to 1 mSv/yr (4 to 100 mrem/yr; DOE, 2009).

If decontamination policy is similar to the approach used after the Fukushima accident, decontamination may occur regardless of property value. However, MACCS only allows decontamination if it is cost effective. This assumes that it is preferable to abandon contaminated properties and perform no decontamination when the cost to restore the property is expected to cost more than the property is worth after the accident. To reflect how some countries are willing to spend amounts many times greater than the property value to restore inhabited areas or to avoid having a permanently restricted, contaminated area, a MACCS user can change or effectively eliminate cost effectiveness considerations by assigning artificially high property values for the region (VALWF and VALWNF). The decontamination cost effectiveness is discussed in Section 4.4.1.

In general, decision makers may make decontamination decisions based on land use. For instance, after the Fukushima accident, Japan would decontaminate uninhabited forest areas only if the forest area bordered an occupied area. MACCS currently only distinguishes farmland and non-farmland as land-use categories, so it cannot distinguish uninhabited land portions of non-farmland. As such, it is up to the user to estimate decontamination costs and dose reduction factors that properly reflect the average land use, especially for regions that contain a variety of land-use categories.

4.1 Cohort Data

The population of a site is typically divided into multiple cohorts so that protective action modeling can reflect how different segments of the population react. Different cohorts can exist in the same spatial element. MACCS has three weighting methods (PEOPLE, SUMPOP, and TIME) to model how multiple cohorts are distributed across the spatial grid and how output results are combined using the parameter WTNAME. These weighting methods are described in Section 1.3.

Cohort modeling is particularly important for the emergency response. Cohorts can represent members of the general public who may evacuate early, evacuate late, refuse to evacuate, those who evacuate from areas not under an evacuation order (i.e., a shadow evacuation), or those who represent special groups such as schools, hospitals, or other institutions that may respond differently than the general public. The use of multiple cohorts allows for more realistic analyses and provides the ability to identify risk at a more discrete level.

MACCS allows up to twenty cohorts in the early phase. In the intermediate and long-term phases, MACCS reduces the population by subtracting the number of early fatalities and treats all survivors from the early phase as part of the same long-term population.

Cohorts can respond differently to many early protective actions. In the evacuation and sheltering model, cohorts can have different evacuation regions, timelines, directions, and speeds. In the KI ingestion model, cohorts can have different KI efficacies and population fractions that ingest KI. The early relocation model largely treats cohorts the same, except cohorts can have different critical organs for dose projection. The early relocation model may apply to different regions for each cohort, but these regions are simply the area in the spatial grid that is not part of the evacuation and sheltering model (i.e., outside the boundary set by the parameter LASMOV). These are discussed in more detail in Section 4.2 on early protective actions.

During the early phase, MACCS assumes that each cohort can be in different states of activity at different points of time. At any point in time, cohorts are in one of the following states: normal activity, sheltering, or evacuating. In the intermediate and long-term phase, there is simply long-term activity, which users typically treat as normal activity. In the evacuation and sheltering model discussed in Section 4.2.1, cohorts in the sheltering and evacuation region change the state of their activity based on the model timeline. The cohort activity affects protection factors and breathing rates. Protection factors and breathing rates are inputs to the dose equations in Section 3.

Cohort Protection Factors

A protection factor is a dimensionless quantity that reduces the dose due to shielding or similar quantity depending on the exposure pathway. MACCS has separate protection factors for each cohort, exposure pathway, and activity.

Dose coefficients assume that individuals are unprotected (i.e., standing outdoors on an infinite flat surface with no obstructions) from exposure to airborne and deposited radioactivity. Protection factors allow the user to account for dose reductions from surface roughness, buildings, and other obstructions. Protection factors should also account for how contamination is distributed (i.e., contamination on trees, rooftops, siding, and in interior areas).

MACCS considers protection factors for each exposure pathway except for ingestion. In the early phase, protection factors also vary for three different states of activity (i.e., evacuation, normal activity, and sheltering). In the intermediate and long-term phases, MACCS assumes just one state of activity (i.e., normal activity). Note that for protective action decisions, MACCS does not have a separate state of activity for calculating projected doses for the phantom receptor and instead uses protection factors for normal activity.

The early phase protection factors for each pathway and each state of activity ℓ is as follows:

- Groundshine Protection Factor ($GSHFAC_{\ell}$) due to shielding
- Cloudshine Protection Factor ($CSFACT_{\ell}$) due to shielding

- Inhalation Protection Factor ($PROTIN_\ell$)
- Skin Deposition Protection Factor ($SKPFAC_\ell$)

In the intermediate and long-term phases, MACCS assumes there is only one population, which uniformly engages in normal activity. While early and long-term protection factors should not change significantly, the ability to use different early and long-term protection factors could be used to reflect how some radionuclides inevitably migrate inside over time. The protection factors for long-term pathways are as follows:

- Long-term Groundshine Protection Factor (LGSHFAC) due to shielding
- Long-term Inhalation Protection Factor (LPROTIN)

These values are inputs into the dose equations discussed in Section 3. The protection factors vary by cohort for several reasons. For instance, the groundshine and cloudshine protection factors may depend on the robustness of the buildings or facilities in which the cohort resides or shelters. Special facilities, such as hospitals or schools, may provide greater shielding than single family dwellings. Cohort specific values may be derived with consideration of the location factors and occupancy fractions appropriate for the cohort. Similarly, the inhalation protection factor and skin deposition protection factors largely come from the difference between indoor and outdoor air concentrations. There is always some air exchange between indoor and outdoor air, but the amount depends on the air tightness, ventilation, and integrity of the building.

Because there is always some air exchange between the indoor and outdoor air, the duration of cloud passage may also be important, with longer times of cloud passage resulting in a smaller difference between interior and exterior concentrations. If the air within the structure is assumed to be well mixed (i.e., the structure is modeled as a single ventilation compartment or the rate of exchange between compartments is high), the location within the building is not as important as it is for protection from sources outside the building.

<u>Cohort Breathing Rates</u>

The breathing rate is the rate that a person inhales a specified volume of air (m^3/s). The breathing rate of an individual in a cohort is proportional to the inhalation dose. Although the breathing rate can vary by age, gender, and activity level, for most analyses an age, gender, and activity-averaged breathing rate is recommended for all activity and for all cohorts for consistency with the inhalation dose factors. The breathing for different states of activity ℓ are as follows:

- Early phase breathing rate ($BRRATE_\ell$),
- Intermediate and long-term phase breathing rate (LBRRATE)

Like the protection factors, the intermediate and long-term phase has just one type of activity, which the user typically treats as normal activity. These parameters are different for each cohort, and they are inputs to the inhalation dose equations in Section 3.

4.2 Early Phase Protective Actions

There are three protective action models for the early phase, (1) the evacuation and sheltering model, (2) the early relocation model, and (3) the KI ingestion model. The evacuation and sheltering model and the early relocation model operate in mutually exclusive and collectively exhaustive areas of the spatial grid, whereas the KI ingestion model can apply to any cohort at any location.

4.2.1 Evacuation and Sheltering Model

MACCS determines where evacuation and sheltering occurs based on a user-specified region and timeline. The timelines can be based on the reactor site conditions, allowing for preemptive evacuations to begin before plume arrival.

For each cohort *i*, the evacuation and sheltering model depends on the value specified for the parameter $LASMOV_i$. $LASMOV_i$ is the boundary beyond which evacuees disappear from the model and receive no further dose. If the user specifies a value greater than zero, MACCS uses the evacuation and sheltering model. A value of zero means the evacuation and sheltering model is not used for that cohort.

When using WinMACCS, the parameter $EVAKEY_i$ controls when $LASMOV_i$ is set to zero. When $EVAKEY_i$ is set to a value of "CIRCULAR" or "KEYHOLE," the user must specify a value greater than zero for $LASMOV_i$, and MACCS uses the evacuation and sheltering model. When $EVAKEY_i$, is set to a value of "NONE," WinMACCS automatically gives $LASMOV_i$ a value of zero, and MACCS does not use the evacuation and sheltering model.

All people outside the evacuation and sheltering boundary (including "non-evacuating" cohorts) are subject to early relocation. Conversely, all people inside the sheltering and evacuation boundary are subject to evacuation but not relocation. As such, all people (including "non-evacuating" cohorts) are subject to removal by the models in the early phase. To make a truly non-evacuating cohort, the user can adjust the early relocation delay parameters (TIMHOT, TIMNRM) or dose criteria parameters (DOSHOT, DOSNRM) to prevent relocation during the early phase; however, these parameters affect all cohorts beyond their evacuation boundary. Alternatively, a user can choose a circular or keyhole model, and increase one of the values in the evacuation timeline (e.g., $DLTEVA_i$, $DLTSHL_i$) so that evacuation does not occur in the region before the end of the early phase (i.e., ENDEMP).

For cohorts in the evacuation and sheltering region, cohort doses include doses they receive before they start evacuating and the doses they receive during evacuation. The evacuation and sheltering timeline assumes that cohorts are first conducting normal activity, then sheltering, and finally evacuation. Cohorts have different protection factors and breathing rates during these times. Evacuees travel to a user-specified distance whereupon they are assumed to avoid further exposure. MACCS assumes that cohorts from outside the evacuation and sheltering region are in normal activity for the duration they occupy a spatial element.

The spatial position of evacuees is a function of time based on the evacuation timeline, direction, and speed discussed in the sections below. For the period that a plume segment in a spatial element is overhead (*TO*), MACCS determines the period that evacuees spend in the spatial element (*TE*). For dose calculations based on time-integrated plume air concentrations (i.e., cloudshine, direct inhalation, and skin deposition), the fraction (*F*) of time that evacuees are exposed to the plume segment ($F = TE / TO$) determines the amount of exposure that evacuees receive in that spatial element. For the other early exposure pathways (i.e., groundshine and resuspension inhalation), the dose integrals directly consider when evacuees enter and exit the spatial element.

4.2.1.1 Evacuation and Sheltering Region

The evacuation and sheltering model can simulate two types of evacuation regions: circular and keyhole. The circular evacuation region is the MACCS default model, where cohorts evacuate from the 360-degree circle around the site. When using WinMACCS, the user can specify a circular evacuation for cohort *i* by setting the parameter EVAKEY_i to “CIRCULAR.” Alternatively, the user can set EVAKEY_i to “KEYHOLE” to use keyhole evacuation, which is described below.

For either evacuation model, the user specifies two boundaries. NUMEVA_i is the outer boundary of the zone for which residents are subject to sheltering and evacuation. LASMOV_i is the outer boundary (equal to or beyond NUMEVA_i) at which evacuees disappear and are assumed to receive no further dose. Users commonly base NUMEVA_i on the size of the emergency planning zone. Even though the default evacuation model is circular, cohorts can be defined to reside in different areas and each cohort can have different evacuation definitions. This gives the user significant flexibility in defining the evacuation and sheltering region.

The keyhole evacuation model is like the circular evacuation model, except that certain areas within the circular area may have a longer delay before evacuation or may not evacuate at all. While all spatial elements within NUMEVA_i can be subject to evacuation, the keyhole model limits the initial evacuation to a smaller, inner circular area and an area downwind of the plume. The motivation behind a keyhole evacuation is to move the population most at risk (close to the plant and downwind) out of the area as quickly as possible without the roadways becoming congested from the population at lower risk. The circular and keyhole models have an identical sheltering region and timeline before evacuation begins.

Figure 4-1 illustrates the location of the different zones of a keyhole evacuation, with the red portion representing the circular portion of the keyhole, the yellow portion representing the central downwind sector, and the orange portions representing the adjacent buffer sectors. The initial downwind sectors (yellow and orange portions) depend on the wind direction. In the simple case with only one wind direction, the evacuation region makes a keyhole shape. MACCS defines the evacuation regions by the radius of inner circular area (KEYDIS_i), the number of compass sectors beyond the inner circular area (NSECTR_i) for a single wind direction, and the outer radius of the evacuation area (NUMEVA_i). As with the circular evacuation model, the outer radius of the evacuation area is usually the emergency planning zone (EPZ) boundary.

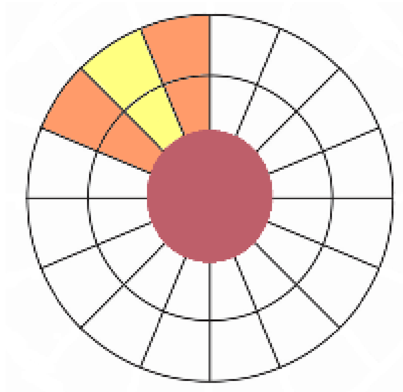

Figure 4-1 Illustration of a Keyhole Evacuation Including Buffer Zones

Outside the inner circular area, a keyhole angle of at least 67.5° is likely appropriate for most analyses. The model requires an equal number of downwind buffer sectors on both sides. When selecting the number of downwind sectors that is appropriate for the downwind evacuation region, the user should consider the angle of a compass sector. For a spatial grid with 16, 32, 48, or 64 total compass sectors, a keyhole angle of at least 67.5° and the requirement that the number of sectors be odd, corresponds to 3, 7, 9, and 13 sectors, respectively.

Table 4-1 Downwind Angle of Compass Sectors

NUMCOR	Degrees (°)/Sector	NSECTR (≥ 67.5°)
16	22.5	3
32	11.25	7
48	7.5	9
64	5.625	13

A shift in the wind direction changes the direction of the next plume segment. As the downwind direction of the plume changes, the keyhole model automatically expands the keyhole region to include the new downwind compass sectors. The evacuation region only expands over time from changing wind directions; it never contracts. When the number of outer sectors reaches half the number of the entire compass, the model assumes the entire circular region evacuates.

Figure 4-2 illustrates a keyhole evacuation region on the MACCS spatial grid considering a shift in wind direction. In this figure, the keyhole evacuation region is initially centered around compass sector 18, as shown by the yellow and purple portion of the keyhole. The number of evacuating compass sectors may expand as the wind direction changes in subsequent hours, as illustrated by the green/orange portion of the expanded keyhole. If the release and the wind shift both occur before evacuation begins, both portions are part of the initial evacuation region.

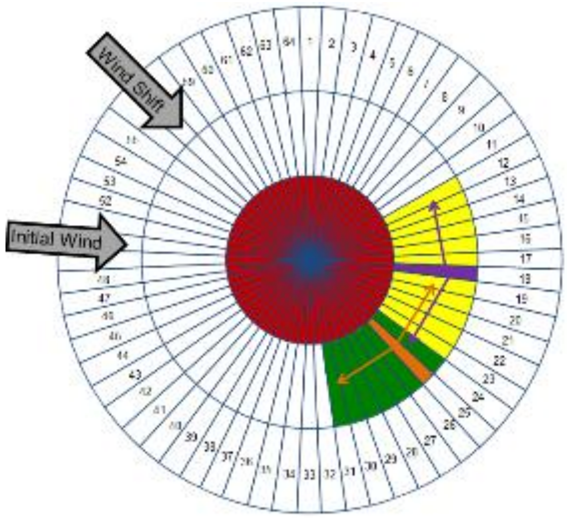

Figure 4-2 Illustration of a Keyhole Evacuation Model

Additionally, based on weather forecasting, decision makers may expand the keyhole evacuation region before a wind shift occurs. MACCS accounts for this and requires the user to specify the number of hours in the parameter KEYFORCST that the keyhole should expand before a wind shift occurs.

If a wind shift will occur anytime between the original evacuation time and KEYFORCST seconds later, the keyhole is immediately expanded to additional compass sectors, also resulting in a wider initial keyhole. For example, when the number of hours is four, the model considers the wind directions that occur over the next four hours and expands the size of the keyhole accordingly.

A wind shift to new compass sectors after this period creates a subsequent evacuation region KEYFORCST hours before the wind shift occurs. When a forecasted wind shift creates a subsequent evacuation region, the population in the expanded area immediately evacuate.

Even though transient weather patterns cannot be forecasted with complete accuracy, the MACCS implementation of the keyhole evacuation region inherently assumes they are. Therefore, the forecast time KEYFORCST should be considered in this light. To consider no advance knowledge of weather, the user should enter a KEYFORCST value of zero.

<u>Evacuation and Sheltering Timeline</u>

Cohorts are subject to shelter and evacuation when they are in the user-defined evacuation and sheltering region discussed in the evacuation model. The period before sheltering occurs depends on a reference point (e.g., an alarm time) and a delay to shelter ($DLTSHL_i$). The period before evacuation begins depends on a reference point, a delay to shelter ($DLTSHL_i$), and a delay to evacuation ($DLTEVA_i$). Figure 4-3 shows a timeline and the associated activity state during each step for a generic cohort.

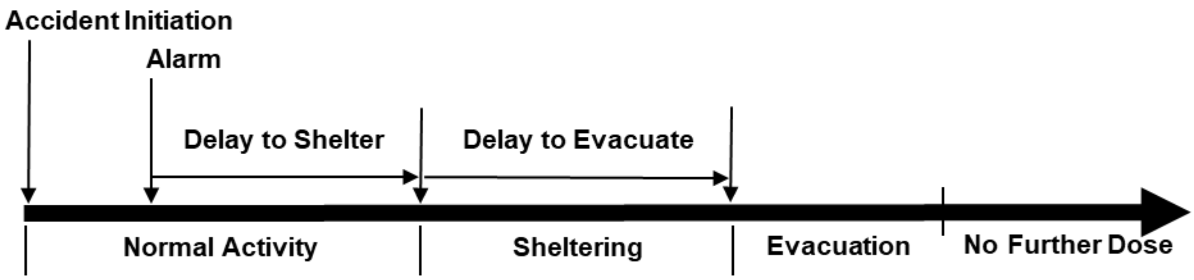

Figure 4-3 Evacuation and Sheltering Timeline for a Generic Cohort

For keyhole cohorts that are in the evacuation and sheltering region set by $NUMEVA_i$, but outside the original keyhole based on the initial wind direction, their delay to evacuation may be longer. Cohorts in the expanded keyhole region evacuate after the user-defined period $DLTEVA_i$ or the point in time when the keyhole is expanded (i.e., when wind shift occurs minus KEYFORCST hours), whichever is longer. Keyhole cohorts that evacuate when $DLTEVA_i$ expires are all part of an initial evacuation region that may be larger than the original keyhole due to forecasted wind shifts.

For cohorts using a circular evacuation model, the user can choose to use a reference point based on either the user-specified alarm time or on the arrival of the first plume segment to the spatial element. The user selects the alarm time option as the cohort's reference point by giving the parameter $REFPNT_i$ a value of "ALARM." The user specifies the alarm time (s) in the parameter OALARM. To select a reference point based on the arrival of the first plume segment to the spatial element, the user specifies a value of "ARRIVAL" to the parameter $REFPNT_i$. In this case, the reference point depends on the atmospheric transport results. Cohorts using a keyhole evacuation model must use the alarm time as the reference point.

The delay to shelter ($DLTSHL_i$) is an additional time period after the reference point before sheltering occurs. The delay to evacuation ($DLTEVA_i$) is the period from the beginning of cohort sheltering until evacuation begins. MACCS requires the user to specify a delay to shelter period and a delay to evacuation period for each evacuating cohort and each radial interval in the evacuation zone. This allows people that are at different distances from the plant to have different sheltering and evacuation timelines, even if they are part of the same cohort.

Users typically treat the alarm time as the notification period between the onset of the accident and the anticipated time that sirens begin. The delay to shelter can then represent the time necessary for the notification of the emergency declaration to reach an average person in the cohort plus the time needed to reach a shelter location. Because of sirens in the evacuation zone and the emergency broadcast system, some people may receive the message almost immediately, while others may not receive the message until after they reach a radio or television, word-of-mouth, or route alerting if applicable. The delay to shelter plus the delay to evacuate is the mobilization time, which is the period from initial notification of the public to evacuate until evacuation begins.

Sheltering may be ordered for specific areas when evacuation cannot be completed prior to arrival of the plume. Sheltering may also be the preferred emergency response for special facilities.

Sheltering followed by evacuation is typically considered the initial protective action for the public living within the plume exposure pathway emergency planning zone (U.S. Nuclear Regulatory Commission, 2011).

To have sheltering and no evacuation, the user can specify a delay to evacuate that is greater than or equal to the duration of the early phase. To have evacuation and no sheltering, the user can specify zero delay to evacuate along with a circular evacuation region. (The circular region is necessary because there may be an additional delay to evacuate with the expanded keyhole regions, depending on the weather forecast.) To have no sheltering or evacuation, the user should not use the evacuation and sheltering model. Even so, MACCS may relocate the cohort, depending on the early relocation dose criteria and time period.

Users should ensure that the protection factors they specify for the different periods are representative of the actions of the cohort. For instance, even though MACCS calls the period before evacuation “sheltering,” this period may be more representative of people preparing to evacuate. While most evacuation preparation is likely to occur inside and have a lower protection factor than normal activity, it could have a higher protection factor than a cohort that is sheltering in a well-shielded basement or more robust building.

4.2.1.2 Evacuation Transit

The evacuation transit for each cohort is split into three travel phases of initial, middle, and late. The initial and middle travel phase durations (s) are defined by DURBEG$_i$ and DURMID$_i$. The late travel phase extends until all individuals have completed their travel or until the end of the early phase, whichever is sooner. The purpose for the evacuation subphases is to allow evacuation speeds to vary over time.

The initial travel phase starts when the earliest population group in the sheltering and evacuation region for a cohort begins to evacuate. This is the radial distance with the smallest total duration for the sum of reference point, delay to shelter, and delay to evacuate.

For the purposes of accounting for dose and health effects, the dose received by an evacuee is attributed to the location in which the evacuee originates. Evacuees travel from the center of one spatial element to the center of another in discreet steps, and dose calculations assume evacuees always reside at a center point of a spatial element. The transit time $T_{t,n}$ provides the residence time of evacuees in spatial element *n* during travel period *t*. The transit time $T_{t,n}$ for an evacuee to move from one grid element to another is determined by several input values.

The starting point for all evacuees is the center of the element in which they reside. For each evacuating cohort i, there are two transit time models that determine the time required for the evacuees to arrive at the next spatial element, as specified by the parameter TRAVELPOINT$_i$. When this parameter is equal to “BOUNDARY,” the evacuee is modeled to be in the next grid element upon crossing the grid boundary. As such, evacuees only need to travel half a spatial element in their initial move. When equal to “CENTERPOINT,” the evacuee is modeled to be in the next grid element upon arrival at the center of the destination spatial element. MACCS uses the following formulae for “BOUNDARY”:

Initial move, moving in or out: $T_{t,n} = \frac{r_n - r_{n-1}}{2 \cdot V_{t,n}}$

Initial move, moving left or right: $T_{t,n} = \pi \cdot \frac{r_n + r_{n-1}}{2 \cdot N_\theta \cdot V_{t,n}}$

After initial move, moving in or out: $T_{t,n} = \frac{r_n - r_{n-1}}{V_{t,n}}$ **(4-1)**

After initial move, moving left or right: $T_{t,n} = \pi \cdot \frac{r_n + r_{n-1}}{N_\theta \cdot V_{t,n}}$

MACCS uses the following formulae for "CENTERPOINT":

Moving out: $T_{t,n} = \frac{r_{n+1} - r_{n-1}}{2 \cdot V_{t,n}}$

Moving in: $T_{t,n} = \frac{r_n - r_{n-2}}{2 \cdot V_{t,n}}$ **(4-2)**

Moving left or right: $T_{t,n} = \pi \cdot \frac{r_n + r_{n-1}}{N_\theta \cdot V_{t,n}}$

Where

- $T_{t,n}$ is the transit time to reach the next spatial element starting in spatial element *n* during travel phase *t*,
- r_n is the outer radius of spatial element *n*, as defined by the parameter SPAEND$_n$,
- $V_{t,n}$ is the speed at which an evacuee moves in spatial element *n* during travel phase *t*, as defined below,
- N_θ is the number of compass sectors in the grid (i.e., 16, 32, 48, or 64), as defined by the parameter NUMCOR.

For radial evacuations (i.e., when the evacuation model EVATYP is set to "RADIAL" instead of "NETWORK"), only radial movements are applicable.

The evacuation speed $V_{t,n}$ is given by the following equations:

$$V_{t,n} = \begin{cases} C_n \cdot V_t & \text{During periods with no precipitation} \\ C_n \cdot C_{weather} \cdot V_t & \text{During periods with precipitation} \end{cases} \quad \textbf{(4-3)}$$

Where

- V_t is the base travel speed of cohort *i* during travel phase *t*, given by the parameter ESPEED$_{it}$,
- C_n is the speed multiplier in spatial element *n* for cohort *i*, given by the parameter ESPGRD$_{in}$, and
- $C_{weather}$ is the speed multiplier due to precipitation for cohort *i*, given by the parameter ESPMUL$_i$.

The base travel speed V_t is the average anticipated speed of evacuees during each travel phase t, assuming no precipitation and is independent of the grid. MACCS requires that all three values of the base travel speed V_t be the same when TRAVELPOINT$_i$ is set to BOUNDARY. For the CENTERPOINT method, the user can modify the travel speed V_t for each travel phase to reflect anticipated traffic congestion during the travel phase.

The spatial element speed multiplier in C_n reflects areas where evacuees may travel faster or slower relative to the base travel speed V_t, based on the type of roadway, number of intersections, the speed of turns, and other slowdowns during normal driving conditions.

The precipitation speed multiplier $C_{weather}$ represents slower speeds and decreased road capacity due to poor driving conditions during adverse weather. Weather prior to release is assumed to be the same as at the beginning of release, which affects cases in which the evacuation begins before release. The occurrence of precipitation is based on the value in HRRAIN, BNDRAN, or the meteorological file, depending on the weather option.

Nuclear power plants in the U.S. are required to develop Evacuation Time Estimates (ETEs) as part of their licensing (10 CFR 50 App. E and 50.47). This information can help to develop appropriate travel speeds and multipliers that reflect travel conditions. Site-specific ETE reports are publicly available in the NRC's record keeping system known as Agencywide Documents Access and Management System (ADAMS). Also available and may be of interest to users is NUREG/CR-7269, which develops ETE data for three representative sites.

4.2.1.3 Evacuation Routing

MACCS has the capability to model an evacuation based on movement in a radial direction away from the plant or based on network evacuation routes. Network evacuation is the preferred approach when evacuation routing information is available. MACCS can model a network evacuation by setting the MACCS variable EVATYP to "NETWORK." The user can use the radial evacuation model by setting the MACCS variable EVATYP to "RADIAL." The user can choose not to model evacuation by setting the number of radial intervals within the evacuation area (LASMOV$_i$) to zero.

<u>Network evacuation</u>

For each spatial element in the evacuation zone, the network evacuation model requires a direction for evacuees to move. The MACCS variable IDIREC$_i$ defines the network evacuation direction for each cohort. IDIREC$_i$ is a matrix with dimensions given by the number of compass sectors (NUMCOR) and radial intervals within the evacuation transit area (LASMOV$_i$). Figure 4-4 shows an example of how directions on a spatial grid form an evacuation network. In the MACCS input file, an IDIREC$_i$ value of 1 indicates an outward evacuation to the next grid element, 2 indicates clockwise evacuation, 3 indicates inward evacuation, and 4 indicates counter-clockwise evacuation. Paths that form loops are not allowed. Paths cannot go through the origin, and there must be at least one outbound path. Each evacuating cohort can have a different evacuation network.

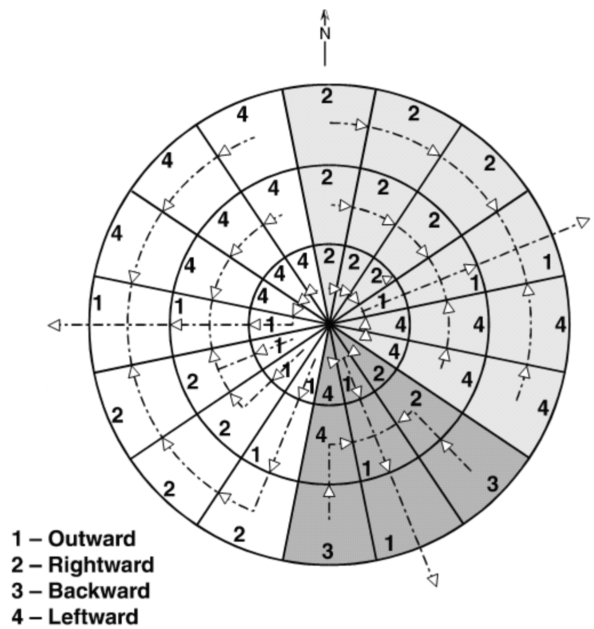

Figure 4-4 Network Evacuation Direction with Corresponding IDIREC Values on a Spatial Grid.

The network evacuation model should represent the actual paths evacuees take along the road network. Evacuation maps for reactor sites can provide users the direction evacuees are likely to follow during the emergency response. When using WinMACCS, the user can define the evacuation routes graphically using a map layer showing roadways. A network evacuation map overlay is illustrated in Figure 4-5.

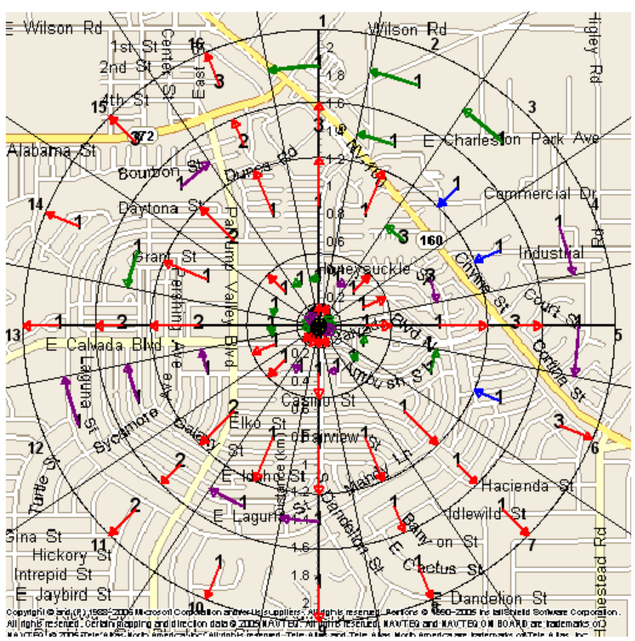

Figure 4-5 Illustration of Network Evacuation Directions

The network evacuation area is mapped onto a grid with the desired number of compass sectors (16 sectors are presented in Figure 4-5 for clarity, but the model may be developed for a 64-sector grid using the same approach).

4.2.2 Early Relocation Model

The early relocation model, which can be thought of as a deferred evacuation, is an emergency response to displace individuals from at-risk areas based on a projected dose and user-specified dose criteria. The use of the term "relocation" to describe a MACCS early phase protective action may be somewhat confusing. EPA guidance and radiological emergency plans make clear that displacement of individuals during the early phase, using early phase dose criteria, is called evacuation. Nevertheless, MACCS uses the term "early relocation" to distinguish this model from the evacuation and sheltering model, and to highlight the fact that early relocation is very similar to the MACCS models for intermediate phase relocation and long-term phase relocation (i.e., habitation restriction).

The early relocation model is intended to cover areas that exceed early phase protective action guides but are not covered by the evacuation and sheltering model. In MACCS, the early relocation model applies to regions outside the boundary set by $NUMEVA_i$, whereas the evacuation and sheltering model applies to regions inside $NUMEVA_i$. Therefore, the early relocation model and the evacuation and sheltering model apply to mutually exclusive and collectively exhaustive areas of the spatial grid. The boundary between evacuation and relocation can be different for different cohorts. A special case is the "non-evacuating" cohort, which effectively has a NUMEVA value defined to be zero. This cohort has no evacuation and sheltering region, so the entire cohort is subject to early relocation.

The early relocation model is based on a projected dose. The projected dose is the lifetime dose to the critical organ ($CRIORG_i$) that occurs between the arrival of the first plume segment and the time after arrival determined by a user-specified dose projection period (DPPEMP). The projected dose is the dose from all plume segments and from the following early dose pathways: cloudshine, direct inhalation, groundshine, and resuspension inhalation.

MACCS evaluates the projected dose in a spatial element against the early relocation dose criteria. If projected dose for a cohort in an area subject to early relocation exceeds either of the two early relocation dose criteria, people are relocated. Note that dose projection in MACCS is based on the same protection factors as normal activity.

There are two different early relocation dose criteria, which create different size relocation areas. The higher dose criterion for a smaller, more urgent relocation is called the hotspot relocation dose (DOSHOT), and lower dose criterion that affects a larger area is called the normal relocation dose (DOSNRM). MACCS requires that the dose for hotspot relocation be greater than or equal to the dose for normal relocation and the delay time for hotspot relocation be less than or equal to the delay time for normal relocation. However, the two criteria can be collapsed into a single criterion by specifying the parameters to be the same for the two relocation types.

Users should first evaluate and consider the size of the area and population affected by different dose criteria before selecting values for DOSHOT and DOSNRM. Depending on the source term and other factors, using strict dose criteria can unknowingly create a relocation area many times larger than the area of the evacuation and sheltering region. Some countries have a range of recommended criteria that provides flexibility for determining the extent of sheltering and evacuation. In the U.S., users typically base early relocation dose criteria on the EPA early phase criteria for evacuation or sheltering, which is "a projected whole-body dose of 1 to 5 rem (10 – 50 mSv) total effective dose over four days" (U.S. Environmental Protection Agency, 2017).

The early relocation timeline of both the hotspot and normal relocation areas depend on the arrival of the first plume segment to the spatial element. During an event, early relocation areas can be difficult to predict a priori (i.e., before plume arrival) based on site conditions because they are commonly beyond the EPZ and would require precise knowledge of the source term, release timing, weather, and other characteristics. After plume arrival, emergency responders can collect and analyze offsite measurements to produce dose projections from existing ground concentrations with reasonable certainty. As such, the dose projection period begins at the arrival of the first plume segment and not before. After plume arrival, TIMHOT and TIMNRM are additional delays for relocation to occur for the hotspot and normal relocation areas, respectively.

Users typically treat the early relocation timeline like the one for the sheltering and evacuation model. The timeline should include the period it takes authorities to declare an emergency for this region, the period necessary for the notification to reach an average person in the cohort, and the period during which people prepare to evacuate. In addition, since relocation is modeled to occur instantaneously at TIMHOT and TIMNRM, at least a portion of the time required to evacuate should also be included. Like the dose criteria, users should also be aware of the size and population of the early relocation area before selecting values for TIMHOT and TIMNRM.

The period before authorities expand the evacuation to an early relocation area is difficult to predict. Time is needed to collect field and aerial measurements, and these measurements may not show a need to evacuate for some time after the arrival of the first plume segment. Even when the necessary information is available, offsite response organizations may delay additional declarations in order to prioritize completing actions in the sheltering and evacuation region before addressing other areas.

The period necessary for the notification to reach an average person in the cohort may also be difficult to predict. While areas outside of the original evacuation and sheltering region may not have sirens, the average person in an early relocation area may be well aware of the evolving accident at the site, due to the additional time before a declaration is made for their region. Users may need to use their best judgment in choosing appropriate times for relocation to occur.

Except for the boundary set by $NUMEVA_i$ and the critical organ set by $CRIORG_i$, the rest of the parameters for the early relocation model treat all cohorts the same. People in the early relocation areas are assumed to be in normal activity before relocation. Thus, the protection factors for normal activity are used. MACCS uses the same protection factors for dose projections and for dose accumulation for the purpose of estimating health effects.

The early relocation model is different from the evacuation and sheltering model in a number of ways. The evacuation and sheltering can occur before plume release while early relocation only occurs after plume arrival. However, setting the relocation time to zero ensures that no dose is accumulated before early relocation occurs. Evacuation and sheltering model applies to a region, whereas, early relocation is evaluated for individual spatial elements. The evacuation and sheltering model simulates dose accumulation during evacuation, whereas the early relocation model does not treat dose accumulation relocation and instead assumes no additional dose for the rest of the early phase.

The MACCS early relocation model is in fact like those of the other phases of the accident. Relocation in the early, intermediate, and long-term phases are all based on a dose projection to a critical organ over a dose projection period, and relocation occurs when this dose projection exceeds a relocation dose for the accident phase. The dose projection criterion used for relocation during the intermediate and long-term phases is commonly referred to as habitability criteria. See Sections 4.3.1 and 4.4.1 for how these are applied in the intermediate phase and long-term phase, respectively.

4.2.3 Potassium Iodide Ingestion Model

Because the thyroid gland bioaccumulates iodine, the thyroid may be particularly susceptible to radioiodine exposures. The purpose of the potassium iodide (KI) administration is to saturate the thyroid gland with stable iodine so that further uptake of radioiodine by the thyroid is diminished. The KI model can simulate the use of KI as a prophylactic. The user can choose to use the KI model by giving the parameter KIMODL a value of "KI," or can turn the KI model off by using a value of "NOKI."

The MACCS KI model assumes that KI ingestion is only effective in reducing early phase thyroid doses from inhaled radioiodine. If taken at the right time, KI can nearly eliminate doses to the thyroid gland from inhaled radioiodine. The effectiveness of KI ingestion depends on the population fraction that receives KI, and the efficacy. The thyroid dose (*Sv*) an individual would receive from inhaling radioiodine $DP_{I,thyroid}$ with KI ingestion is the following:

$$DP_{I,thyroid} = (1 - \varepsilon_{KI}) \cdot DB_{I,thyroid} \tag{4-4}$$

Where

- $DB_{I,thyroid}$ is the thyroid dose (*Sv*) from radioiodine through the inhalation pathways that an individual would receive with no KI ingestion using standard dose coefficients, and

- ε_{KI} is the efficacy of the KI tablets in reducing thyroid doses from radioiodine where a value of one is complete protection and a value of zero is no protection specified by the parameter $EFFACY_i$.

KI protection is only applicable to the fraction of the cohort that ingests KI tablets. When KI protection is modeled, cohorts are further subdivided between those that ingest KI tablets and those that do not according to the parameter $POPFRC_i$. When using a non-LNT dose-response model, the population fraction for KI ingestion must be either zero or one. If desired, a user can instead choose to model the two groups as separate cohorts.

Factors that contribute to the efficacy of KI include the ability of residents to find their KI or to obtain KI during the emergency, the timing of ingestion, and the degree of pre-existing stable iodine saturation of the thyroid gland.

4.3 Intermediate Phase Protective Actions

The intermediate phase begins immediately after the early phase. In MACCS, the phases are discrete (i.e., they cannot overlap). For MACCS to consider their impact, all early responses must be taken and all releases must be complete by the end of the early phase. The user can define the duration of the intermediate phase for any period between zero and thirty years with the parameter DUR_INTPHAS. The only response considered during the intermediate phase is habitation restrictions (i.e., relocation), which are for areas where doses exceed the intermediate phase habitability criterion. Note that the intermediate phase criterion is different than either the early or long-term criterion, and the number of people displaced in either the early phase or long-term phase can be larger or smaller.

The user can choose not to model the intermediate phase by giving the parameter DUR_INTPHAS a value of zero. In this case, the long-term phase begins immediately after the early phase. When the user models an intermediate phase, the intermediate phase extends the period before long-term phase actions like decontamination begin. The longer period also reduces the area subject to long-term protective actions. This is because radioactive decay and natural weathering continue during the intermediate phase, and long-term protective actions are based on projected doses that begin at the start of the long-term phase. The intermediate phase period does not affect the food and water ingestion period, although they are usually discussed as belonging to the long-term phase.

MACCS models the accident phases independently of each other. At the end of the intermediate phase, intermediate habitability restrictions are immediately lifted and are immediately followed by the long-term habitability restrictions in the long-term phase. This can cause some unintended discontinuities compared to how authorities would manage habitation restrictions in contaminated areas. If the long-term phase has a larger area than the intermediate phase, then some areas where people were residing during the intermediate phase suddenly become restricted and require decontamination. If instead the area of the intermediate phase is larger, people immediately return to some areas previously deemed uninhabitable before decontamination or other measures occur. In Fukushima, evacuation orders were not lifted until after the completion of decontamination and other criteria were met. Most countries including the U.S. are unlikely to have separate intermediate and long-term habitability criteria. A user can avoid these issues by simply choosing not to model an intermediate phase.

4.3.1 Intermediate Habitation Restrictions

The intermediate phase habitation restrictions (i.e., relocation) is the protective action that displaces individuals based on a projected dose and a user-specified dose criterion. Habitation restrictions during the intermediate phase limit radiation exposure from radionuclides deposited on the ground and other surfaces and can be implemented in a more selective manner to protect only the at-risk population, compared to during an urgent evacuation for which the at-risk population is not clear.

The intermediate phase projected dose is the lifetime dose to the long-term critical organ (CRTOCR) during the intermediate phase dose projection period (DPP_INTPHAS) from groundshine and inhalation of resuspended contamination. MACCS evaluates the projected dose against the intermediate phase habitability dose criterion (DSCRTI). If projected doses exceed the habitability criterion, people in the spatial element are relocated for the duration of the intermediate phase and receive no further dose before the long-term phase.

4.4 Long-Term Phase Protective Actions

The long-term phase begins at the end of the intermediate phase or at the end of the early phase if the intermediate phase is excluded by setting its duration to zero. The long-term phase separates the consequences associated with (1) inhabited land (i.e., non-farm areas), and (2) agricultural land (i.e., farm areas).

In general, there are just two types of long-term protective actions: decontamination and interdiction. However, “interdiction” can refer to habitation restrictions (i.e., long-term relocation), farming restrictions, or both, depending on the context.

From contamination in non-farm areas, MACCS models consequences from groundshine and resuspension inhalation. Protective actions against groundshine and resuspension inhalation may include a combination of decontamination and habitation restrictions. When habitation restrictions are in place, people receive no doses (apart from worker doses during decontamination) and interdiction costs occur, as discussed in Section 6. MACCS does not model ingestion of food that comes from gardens or foraged in non-farm areas.

From contamination in farm areas, MACCS models consequences from food ingestion. While ingestion does not occur in farm areas, MACCS assumes contaminated food from farm areas enters the food supply unless it is restricted. There are two food ingestion models, those being the original MACCS food-chain model and the COMIDA2 food-chain model. Protective actions include farming restrictions, which occurs when doses or ground concentrations exceed farmability criteria, but the implementation of these restrictions differs between the two models. Farming restrictions also occur when farmland exceeds the habitability criterion, as MACCS assumes farmland is otherwise not farmable. As such, the habitability criterion indirectly protects against food ingestion dose as well. Farming restrictions are discussed in more detail in Section 4.4.2.

From contamination in both non-farm and farm areas, MACCS also models consequences from drinking water ingestion and doses to decontamination workers but does not consider protective actions for either (i.e., it assumes all drinking water is consumed).

The phrases “condemnation” and “crop disposal” are commonly used in this report and elsewhere. In MACCS, the costs of “permanent interdiction” is treated as if the property were “condemned,” and therefore the terms are sometimes used interchangeably. “Crop disposal” refers to a protective action to interdict crops from farm areas for the current season. The impact of crop disposal is that it causes an economic farming loss of revenue for the current season that began before the accident occurred. This is to clarify that this is not simply an additional cost for dealing with contaminated waste.

Decontamination

Decontamination of a spatial element serves to reduce the dose to individuals who reside there, which comes from the groundshine and resuspension inhalation pathways. Decontamination may occur in both non-farm and farm areas to help restore habitability, but MACCS assumes that decontamination does not decrease food ingestion doses. Whether or not decontamination would realistically reduce food ingestion doses depends on the decontamination methods. Methods that remove contamination generally would reduce food ingestion doses, while other methods that simply increase shielding (e.g., plowing) may only have a minimal effect on food doses.

The user can specify up to three different levels ℓ of decontamination. The dose reduction factor DRF_ℓ (dimensionless) for decontamination level ℓ is a value that the user specifies in the parameter $DSRFCT_\ell$. The DRF_ℓ are linear scaling factors by which the doses are reduced due to decontamination. For example, a dose reduction factor of three indicates that two-thirds of the radioactive material is removed as a result of the decontamination process. The DRF_ℓ are inputs to long-term dose equations in Section 3.4. The decontamination cost for decontamination level ℓ is a value that the user specifies through the parameter $CDNFRM_\ell$ for non-farm areas (*$/person*) and $CDFRM_\ell$ for farm areas (*$/hectare*). The decontamination costs are inputs to the cost equations in Section 5.3.

During decontamination, the land is assumed to be interdicted. The dose reduction during a decontamination period is twofold: (1) the dose reduction due to decontamination, and (2) dose reduction due to weathering and radioactive decay during interdiction. The influence of these two factors are assumed to be independent. That is, if the user specifies a DRF_ℓ of 3 and a decontamination period of 1 year, and if MACCS calculates a twofold reduction from weathering and decay during this time period, the combined effect would be a reduction in groundshine and resuspension inhalation doses by a factor of six.

Decision Criteria

MACCS decides the location of long-term protective actions according to three independent evaluations: (1) an evaluation related to whether land at a specific location and time is suitable for human habitation, based on a "habitability criterion," (2) an evaluation related to whether land at a specific location and time is suitable for agricultural production, based on “farmability criteria,” and (3) an evaluation that limits the use of decontamination when costs exceed property values, known as the “cost-effectiveness” evaluation.

MACCS treats the habitability criterion as a dose threshold that restricts the public from safely occupying an area. Therefore, MACCS applies the habitability criterion to both farm and non-farm areas. Even though farm areas are assumed not to be inhabited, MACCS does not allow a farmer to work on a farm that exceeds the habitability criterion. As such, agricultural use of farm areas can be restricted by either farmability or habitability criteria, while use of non-farm areas is only restricted by the habitability criterion. MACCS uses the farmability criteria to help evaluate when farming restrictions are necessary to prevent food ingestion doses and are different for the two food-chain models. These are discussed in more detail in Section 4.4.2.

In MACCS, the goal of decontamination is to reduce the habitation doses below the long-term dose criterion using the minimal decontamination effort that would be successful. As such, the location of decontamination is limited to areas that exceed the habitability criterion, which can occur in either farm or non-farm areas. Regardless of decontamination, MACCS assumes people receive no dose during interdiction and do not return until ambient doses are below the habitability criterion. Therefore, the decontamination model does not significantly lower the dose that the public would otherwise receive, but decontamination may help restore habitability of areas more quickly. MACCS assumes that decontamination lowers groundshine and resuspension inhalation doses (i.e., doses in non-farm areas) but not food ingestion doses (i.e., doses from farm areas). Likewise, while decontamination can occur in farm areas, it is only performed to restore habitability.

MACCS may further limit the location of decontamination to areas that are "cost effective." MACCS assumes no decontamination in condemned areas and that condemnation is a preferable option when condemning an area costs less than restoring habitability. This cost-benefit decision is discussed in more detail in Section 4.4.1.

4.4.1 Long-Term Habitation Restrictions

Habitation restrictions can affect both farm and non-farm areas. This section is applicable to both land use areas when there are no farming restrictions in farm areas. Farming restrictions create additional considerations discussed in Section 4.4.2. Figure 4-6 shows the MACCS decision process for areas that may be affected by habitation restrictions.

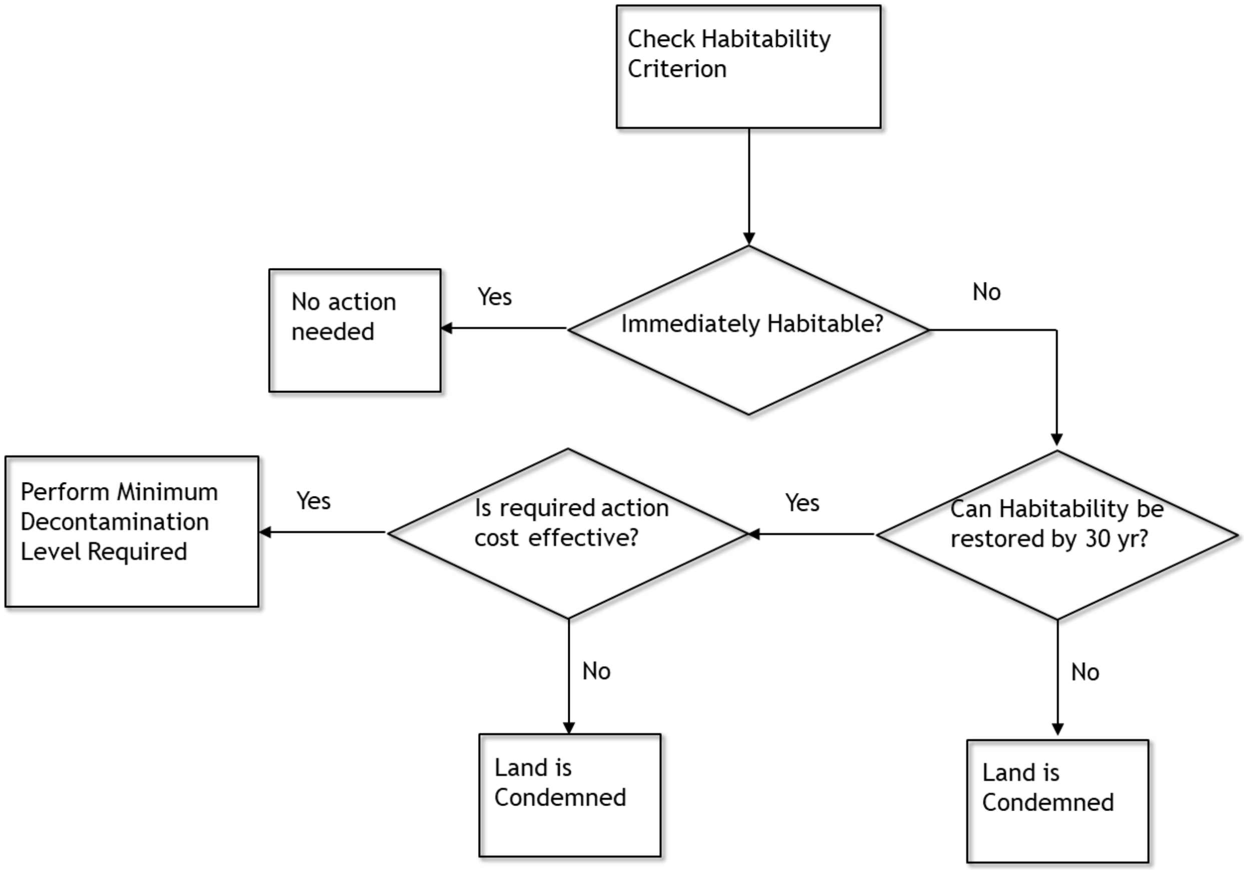

Figure 4-6 Flowchart for Areas Affected by Habitation Restrictions (Assuming No Farming Restrictions)

Figure 4-7 shows an illustration of the anticipated doses received for different long-term protective actions. The purple line is the ambient dose in an area and the dose people would receive assuming no protective actions are taken. The lines below the purple line are doses people would receive assuming increasingly aggressive protective actions. The thick black line is the resulting dose the public receives after applying the decision logic that MACCS uses for selecting a long-term protective action level. The black line assumes the land is always cost effective to decontaminate and assumes the land is not farmland restricted due to farmability.

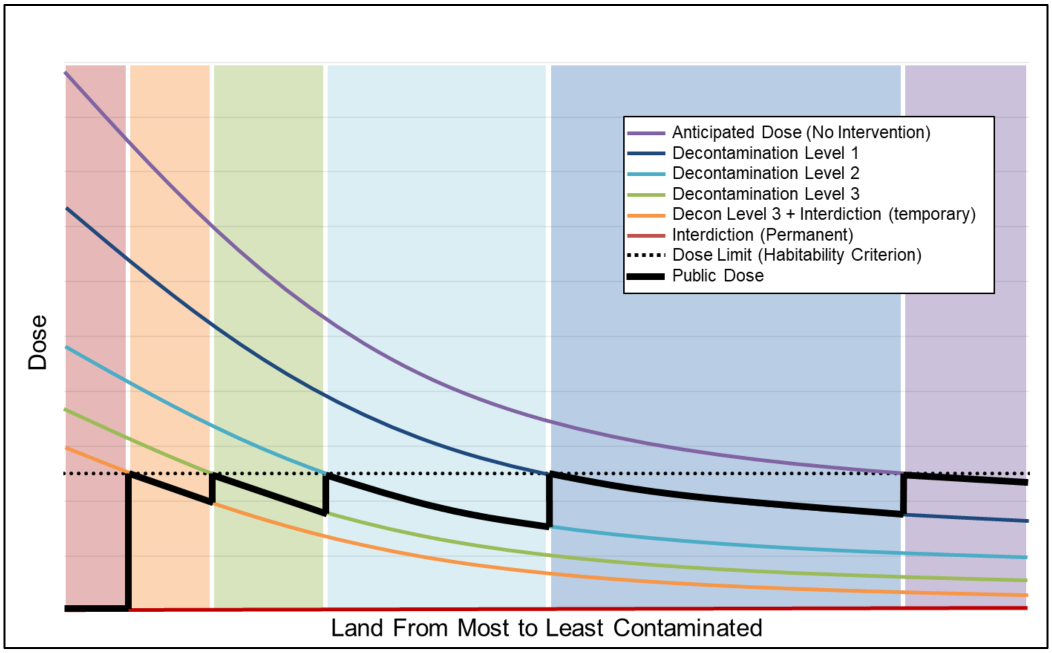

Figure 4-7 Doses Received After Long-Term Protective Actions

Protective action levels for habitation restrictions can result in four possible outcomes: (1) land is immediately habitable, represented by the purple region, (2) land is habitable immediately after decontamination, represented by the blue and green regions, (3) land is habitable after decontamination and an additional period of interdiction, represented by the orange region, and (4) land is condemned with removal and resettling of the population, represented by the red region. Areas represented by the orange, green, and two blue areas can also become condemned if it is not cost effective to decontaminate. In this case, the dose in these areas is zero (the red line). (An area that is permanently interdicted is treated as if the area is "condemned," and therefore the terms are used interchangeably.)

(1). Land Immediately Habitable

The first decision in the Figure 4-6 is to determine whether, in the absence of any protective actions, the land is suitable for habitation during the long-term exposure period. This is done by comparing the projected individual dose to the critical organ (CRTOCR) during the long-term dose projection period (TMPACT) against the user-specified dose criterion for long-term exposure (DSCRLT), commonly referred to as the habitability criterion. If the projected individual dose does not exceed DSCRLT, then the land is considered immediately habitable, and no further tests regarding habitability are made. This means that the dose exposure duration (EXPTIM) begins at the start of the long-term phase, and there are no costs resulting from habitation restrictions.

(2). Land Habitable after Decontamination

If land is not immediately habitable, the next decision in Figure 4-6 is to determine whether an area can be made habitable with decontamination and interdiction before the end of the maximum interdiction period for the area. This is the same habitability evaluation as before, except MACCS calculates the projected dose accounting for the maximum possible dose reduction DRF_{max} and a dose projection period (TMPACT) that begins after decontamination ($TIMDEC_{max}$) and the maximum period of temporary interdiction. The maximum period of temporary interdiction is 8 years for farm areas and 30 years for non-farm areas. If the area cannot be made habitable by the end of the maximum period of temporary interdiction, the area is immediately condemned, and no further evaluation is necessary. If an area is condemned, there is no long-term exposure period, and there are condemnation costs as discussed in Section 5.3.

If the land can be made habitable, MACCS evaluates a progressive series of actions to select a decontamination option to restore the area, and then MACCS proceeds to evaluate whether that option is more cost effective than condemnation. The evaluation for cost effectiveness is shown in Figure 4-6 and discussed below.

MACCS begins by evaluating the first user-defined decontamination level, which is the level that requires the smallest effort but has the smallest dose reduction factor, DRF_1. These actions and their effect on the dose from the groundshine and resuspension inhalation pathways can be seen in Figure 4-7. MACCS evaluates the dose reductions and selects the decontamination level that can reduce habitation doses to acceptable levels with the minimum amount of effort. If the maximum-level decontamination effort is insufficient, MACCS consider additional interdiction as discussed below.

When decontamination occurs (with no additional interdiction period), MACCS assumes people return after decontamination is complete. The decontamination duration ($TIMDEC_{\ell}$) begins at the start of the long-term phase and may be different for each decontamination level, ℓ. Interdiction costs accumulate during the decontamination period, and the dose exposure duration (EXPTIM) begins after the decontamination period $TIMDEC_{\ell}$ is complete.

(3). <u>Land Habitable after Decontamination and Interdiction</u>

If the maximum-level decontamination effort is insufficient to allow habitability at the conclusion of the decontamination period, MACCS determines the duration of an additional interdiction period necessary to restore habitability. If an additional interdiction period is sufficient, MACCS assumes that people return after the additional interdiction period. Interdiction costs accumulate for the full interdiction period ($TIMDEC_{max}$ + additional period), and the dose exposure duration (EXPTIM) begins after this full interdiction period.

MACCS calculates the effect of weathering and decay over set intervals of 1, 5, and 30 years after the completion of the maximum-level decontamination effort. To estimate the time at which a spatial element is projected to satisfy the habitability criterion, MACCS uses a log-linear interpolation technique, which is to say the interpolation is linear on time and logarithmic on dose. The log-linear interpolation assumes that the dose to the population following a period of interdiction follows a pattern of exponential decay as a function of time. This allows MACCS to determine the point in time doses no longer exceed habitation restrictions, which may be a partial number of years. This contrasts with the evaluation of farming restrictions, which MACCS performs for discrete annual periods. Since the COMIDA2 food-chain model evaluates food ingestion doses annually, farm areas are restricted for whole number of years, regardless of whether those restrictions are due to habitation or farming restrictions.

Decontamination Cost Effectiveness

If the area is not initially habitable but can be made habitable before the maximum interdiction period ends, MACCS evaluates the benefit of decontamination before allowing decontamination to proceed. If the cost of decontamination and the anticipated interdiction losses are greater than the condemnation losses, the property is condemned. The evaluations of the decontamination cost effectiveness are different for non-farm and farm areas:

$$\text{Non-farm areas:} \quad CD_\ell^{NF} + CF + CC^{NF} \geq VW^{NF} + CF$$
$$\text{Farm areas:} \quad CD_\ell^{F} + CC^{F} \geq VW^{F} \qquad \textbf{(4-5)}$$

Where

- CD_ℓ^{NF} and CD_ℓ^{F} are the decontamination costs of the minimum decontamination level ℓ that can restore habitability in non-farm areas (*$/person*) and farm areas (*$/hectare*), as specified by the parameters CDNFRM_ℓ and CDFRM_ℓ respectively,

- CC^{NF} and CC^{F} are the costs from loss of use and depreciation for non-farm areas and farm areas, respectively, as discussed in Section 5.3,

- VW^{NF} and VW^{F} are the value of wealth in non-farm and farm areas, as specified by the parameters VALWNF and VALWF, respectively, and

- CF is the one-time cost to relocate (*$/person*) an individual in the long-term phase.

The left-hand side of these inequalities are the costs that are incurred when decontamination is necessary. The right-hand side are condemnation costs. For non-farm areas, the cost to relocate an individual CF contributes to both sides, and so it cancels out. Farm areas do not have this term, since MACCS assumes that people only reside in non-farm areas.

Higher values for VALWNF and VALWF make decontamination more likely and condemnation less likely. While VALWNF and VALWF are traditionally the average offsite property values, as implemented in MACCS, these parameters represent the amount that society is willing to pay to make these contaminated areas habitable again. At a minimum, the user should specify values that are at least equal to the average land and property values before the accident. However, some countries are willing to spend amounts many times greater than the property value to restore inhabited areas or to avoid having a permanently restricted, contaminated area. When VALWNF and VALWF exceed the average property values, decisions to cleanup an area can treat contaminated properties as being a liability when condemned. Increased values for these parameters are supported by the cleanup of Superfund sites in the U.S., which show a willingness to perform cleanup when costs far exceed property values alone. Likewise, Japan is working to restore all contaminated areas even when costs exceed property values, including the reactor site.

4.4.2 Long-Term Farming Restrictions

There are two food dose ingestion models, each with their own set of protective actions, but share the same set of economic costs. The user can choose the COMIDA2 food-chain model by giving the MACCS parameter FDPATH a value of "NEW," or can choose the original food-chain model by using a value of "OLD". A value of "OFF" turns off both models, in which case there are no ingestion doses or dose restrictions. MACCS does not model drinking water restrictions.

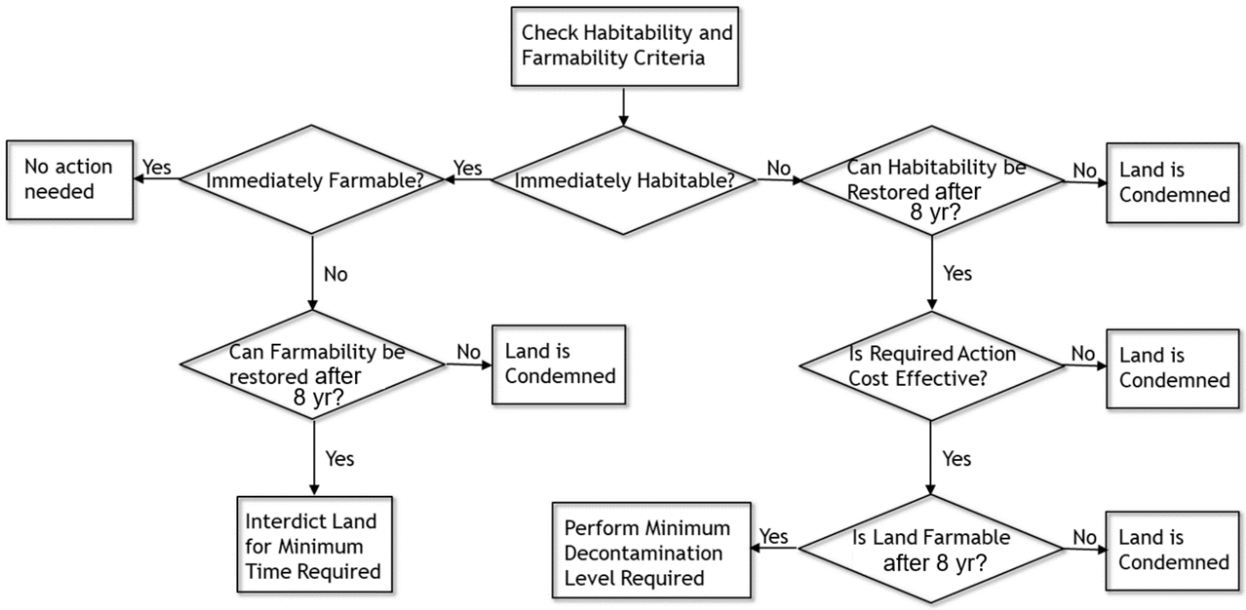

Figure 4-8 Logic Flowchart for Farmland Restrictions

Figure 4-8 is a simplified logic diagram for farmland restrictions. Regardless of the food ingestion model, a fundamental constraint on food production in contaminated areas is that the land must be habitable for it to be farmable. Farming restrictions are always subordinate to the code's evaluation of habitability. That is, when land is subject to habitability restrictions because projected groundshine and resuspension doses exceed the long-term dose criterion, DSCRLT, farming is not allowed.

If a farm area is not immediately habitable, it must become habitable before the code considers lifting the farming restrictions. If it is not possible to restore farmability, MACCS simply condemns the farm area and assumes no effort is given to restore habitability. Otherwise, MACCS uses the same process for lifting habitability restrictions in both farm and non-farm areas, which is discussed in Section 4.4.1. Decontamination can occur in farm areas, but only to help restore habitability and only if it is cost effective, just as in non-farm areas. Decontamination does not reduce food ingestion doses or the minimum interdiction period required for farmability. Ultimately, the total farm interdiction period is the larger one of two time periods: (1) the minimum farm interdiction period due to farmability criteria, or (2) the habitation restriction period.

4.4.2.1 Original Food-Chain Model

The original MACCS food-chain model considers two kinds of food ingestion pathways, a growing season pathway and a long-term pathway. MACCS considers protective actions for each, those being (1) restrictions for the current growing season (i.e., disposal of already growing crops, referred to as "crop disposal"), and (2) restrictions of long-term farm production. Crop disposal is a one-time action and refers to crops the farmer began growing before the accident but is not allowed to bring to market after they become contaminated. As such, crop disposal is only applicable when the accident occurs during a growing season. The restriction of long-term farmland production is independent of the time in the year when the accident occurs and may be required for multiple years.

The user can choose to model growing season pathway and long-term pathway in one of two modes. If the user gives the parameter COUPLD a value of "FALSE," MACCS models the growing season pathway and the long-term pathway independently (i.e., uncoupled). In this mode, the occurrence of crop disposal and long-term restrictions do not affect each other. If the user instead gives the parameter COUPLD a value of "TRUE," a first-year farming restriction in the long-term pathway automatically triggers a disposal of both milk and non-milk crops, and likewise a disposal of both milk and non-milk crops automatically triggers a first-year farming restriction in the long-term pathway. This is described in more detail in the sections below.

For the current growing season pathway, MACCS divides farm production into two categories: milk and non-milk crops. Milk refers to the portion of crops necessary to produce both fresh milk as well as dairy products such as cheese and butter, and non-milk crops refers to all other crops. MACCS evaluates milk and non-milk crop disposal separately for each spatial element. For the long-term pathway, MACCS evaluates farm production as a single category and either allows or restricts all farm production in the spatial element.

The original food-chain model has three types of farmability criteria, all of which are governed by user specified parameters in terms of a maximum permissible ground concentration (Bq/m^2). PSCMLK_i and PSCOTH_i define the maximum permissible ground concentrations for milk and non-milk crops, respectively, of food ingestion radionuclide *i* for the current growing season pathway. These farmability criteria are only applicable when the accident occurs during the growing season. For high levels of contamination, it may be necessary to restrict farming for several years after the accident. GCMAXR_i defines the maximum permissible ground concentration of food ingestion radionuclide *i* for all crops in the long-term food pathway.

While these farmability criteria provide the maximum allowable ground concentrations for a single radionuclide, there may be many food ingestion radionuclides. The list of radionuclides considered in the original food-chain model is specified in the parameter NAMIPI_i, which must be a subset of the radionuclides considered in the transport model specified in the parameter NUCNAM_i. The next sections discuss how MACCS uses the farmability criteria to determine milk and non-milk crop disposal and long-term farming restrictions.

Growing Season Ingestion Pathway

When the new growing season begins before an accident occurs, farmers may be required to dispose of the crops that they are currently producing. MACCS automatically triggers crop disposal under either of the following conditions:

(1). when a farm area is not immediately habitable (i.e., habitation doses exceed DSCRLT in the first year of the long-term phase), or

(2). when the first year of the long-term ingestion pathway requires farm interdiction (i.e., when $RS_{t=0}$ in Equation (4-8) is greater than one; assuming models are "coupled")

Condition (2) is only applicable if the user couples the growing season pathway and long-term food pathway (i.e., COUPLD = "TRUE"). If MACCS has not already required crop disposal because of one of these conditions, MACCS evaluates whether crop disposal should occur because ground concentrations exceed permissible levels for food consumption. For this, MACCS evaluates milk crops and non-milk crops separately.

In general, milk or non-milk crop disposal is required when a ground concentration of any single radionuclide exceeds its permissible level for milk or non-milk crops, respectively. However, the actual ground concentrations in a spatial element may include a mixture of radionuclides. Therefore, the evaluation for when ground concentrations exceed an overall permissible level is based on a sum of ratios in which each ratio measures how close a food ingestion radionuclide is to exceeding its maximum permissible level.

In each spatial element, the milk dose ratio *MDR* is the sum of ratios measuring how close food ingestion radionuclides are to exceeding a permissible level for milk production. The milk dose ratio *MDR* is calculated using the following equation:

$$MDR = \sum_i \left(\frac{GC_i}{PSCMLK_i} \right) \tag{4-6}$$

Where

- MDR is the milk dose ratio,
- GC_i is the ground concentration (*Bq/m*^{2}) of the food ingestion radionuclide *i* in a spatial element, calculated by Equation (3-7),
- $PSCMLK_i$ is the user-specified maximum permissible ground concentration (*Bq/m*^{2}) of radionuclide *i* for milk production.

When the milk dose ratio *MDR* exceeds a value of one, milk disposal occurs. Milk disposal within a spatial element assumes an interruption of milk products for one-fourth of a year. This period is hard-coded into MACCS and is based on the growing season being about one-half of a calendar year and the fact that an accident that does occur during the growing season would on average occur in the middle. For any value of *MDR* less than one, there is no milk disposal (except under the conditions discussed above), and an associated ingestion dose can result from that spatial element.

In each spatial element, the non-milk dose ratio *NMDR* is sum of ratios measuring how close food ingestion radionuclides are to exceeding a permissible level for non-milk crop production. The non-milk dose ratio *NMDR* is calculated using the following equation:

$$NMDR = \sum_i \left(\frac{GC_i}{PSCOTH_i} \right) \tag{4-7}$$

Where

- $NMDR$ is the non-milk dose ratio,
- GC_i is the ground concentration (Bq/m^2) of the food ingestion radionuclide i in a spatial element, calculated by Equation (3-7),
- $PSCOTH_i$ is the user-specified maximum permissible ground concentration (Bq/m^2) of radionuclide i for non-milk production.

When the non-milk dose ratio *NMDR* exceeds a value of one, all non-milk crops are disposed of within that spatial element for one growing season. For any value of *NMDR* less than one, there is no disposal of these crops (except in the conditions discussed above), and an associated ingestion dose can result from that grid element.

<u>Long-Term Ingestion Pathway</u>

Regardless of whether the accident occurs during the growing season, contaminated soil may require farm interdiction to restrict future crop production. MACCS automatically triggers long-term farm interdiction when either of the following conditions apply:

(1). when a farm area is not habitable (i.e., habitation doses in the long-term phase exceed DSCRLT), or

(2). when the growing season ingestion pathway requires both milk and non-milk crop disposal (i.e., both *MDR* and *NMDR* are greater than one; first year only; assuming models are “coupled”)

Habitability restrictions cause farm interdiction each year that habitability is restricted, whereas growing season crop disposal only causes farm interdiction in the first year and only when the user couples the growing season pathway and long-term food pathway (i.e., COUPLD = “TRUE”). If a farm area is immediately habitable, for each year after the accident, MACCS evaluates whether farming should be restricted in order to limit doses from the long-term ingestion pathway.

Like the growing season pathway, the long-term ingestion pathway evaluates when ground concentrations exceed an overall permissible level based on a sum of ratios, where each ratio measures how close a food ingestion radionuclide is to exceeding its maximum permissible level.

The model evaluates the long-term pathway each year after the accident, accounting for weathering and decay. In each spatial element, the overall ratio RS for the long-term ingestion pathway is calculated each year after the accident using the following equation:

$$RS_t = \sum_i \left(\frac{GC_i \cdot exp[-t \cdot \lambda_i]}{GCMAXR_i} \right) \tag{4-8}$$

Where

- RS_t is the overall ratio in the spatial element *t* years after the accident,
- GC_i is the ground concentration (Bq/m^2) of the food ingestion radionuclide *i* in a spatial element, calculated by Equation (3-7),
- t is the number of years (an integer) after the end of the early phase, (i.e., $t = 0$ is the beginning of the first year, $t = 1$ is the beginning of the second year, etc.),
- λ_i is the weathering and radiological decay constant (yr^{-1}) of radionuclide i, given by the user-specified parameter $QROOT_i$, and
- $GCMAXR_i$ is the user-specified maximum permissible ground concentration of radionuclide *i* for long-term farm production (Bq/m^2).

MACCS calculates RS_t for values of t ranging from zero to a maximum of eight years (a fixed value), and $RS_{t=0}$ is used to evaluate the first year. When the value of RS_t is greater than one, farm production in the spatial element is restricted that year. The first year *t* in which RS_t is less than or equal to one is the minimum farm interdiction period *MINYRS*. A *MINYRS* value of eight years is the maximum period of *temporary* farm interdiction. If RS_t is greater than one for all integer values of *t* between zero and eight, the value of *MINYRS* is set to nine and the farm area is permanently condemned. (*MINYRS* is an internal parameter in the code and is not user-specified.)

Coupled and Uncoupled Options

Figure 4-9 and Figure 4-10 show the logic diagrams of the uncoupled and coupled options, respectively, for the growing season ingestion pathway. *MDR* and *NMDR* are the milk dose ratio and non-milk dose ratio in Equations (4-6) and (4-7) used to evaluate the respective exceedance of permissible ground concentrations of milk and non-milk crops for the growing season ingestion pathway. *MINYRS* is the minimum number of years of farm interdiction for the long-term ingestion pathway, as discussed in the previous section.

For the "uncoupled" option in Figure 4-9, milk and non-milk crop disposal only depend on habitability and whether *MDR* and *NMDR* are greater than a value of one. *MDR* and *NMDR* do not affect the minimum number of years for farm interdiction.

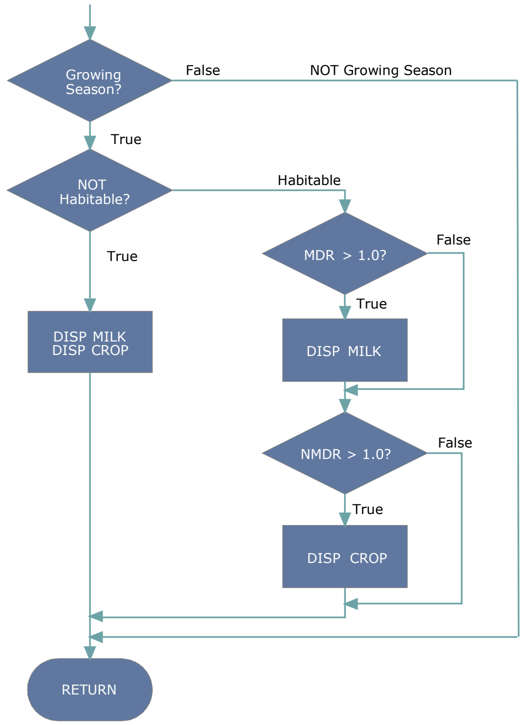

Figure 4-9 Growing Season Logic Diagram of the Uncoupled Option in the Original Food-Chain Model

For the "coupled" option in Figure 4-10, milk and non-milk crop disposal are like they were before, but now they also depend on *MINYRS*. In this option, a *MINYRS* value other than zero automatically triggers disposal of both milk and non-milk crops. Also, when both *MDR* and *NMDR* are greater than one, *MINYRS* is automatically given a value of one, causing a minimum farm interdiction period of one year.

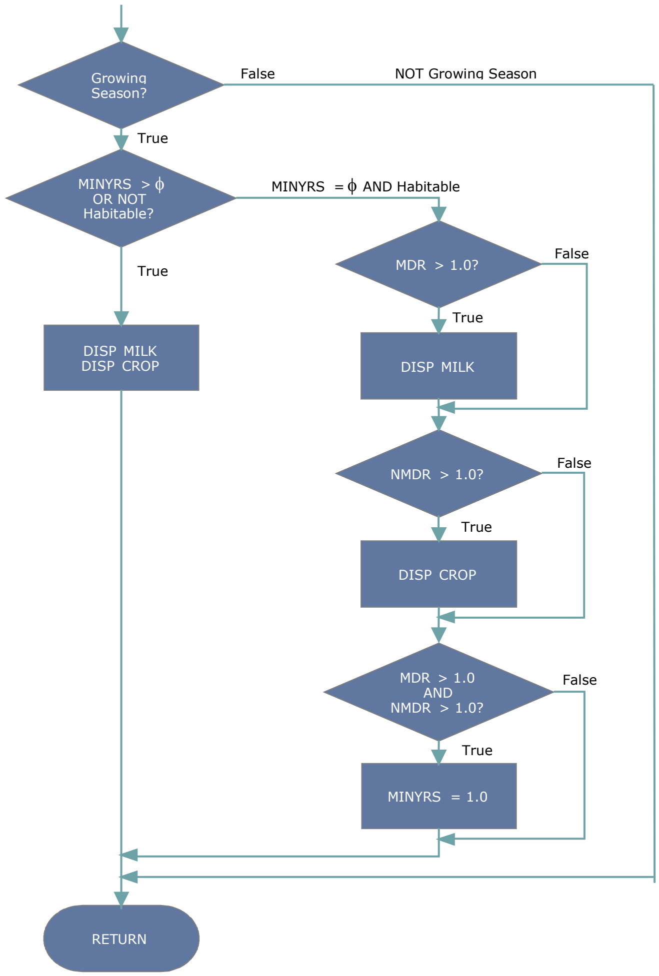

Figure 4-10 Growing Season Logic Diagram of the Coupled Option in the Original Food-Chain Model

4.4.2.2 COMIDA2 Food-Chain Model

The protective actions implemented in the COMIDA2-based food-chain model was developed with the intent that they be as close as possible to the original MACCS food-chain model. The original MACCS food-chain model has two sets of protective actions, one for the growing season ingestion pathway and the other for the long-term ingestion pathway. Because the COMIDA2 food-chain model has just one ingestion pathway, protective actions in the first year of the COMIDA2 model are treated like the growing season pathway, and protective actions in the following years are treated like the long-term pathway. Unlike the original food-chain model, the COMIDA2 model evaluates the need for milk and non-milk crop disposal regardless of whether the accident occurs during the growing season or not.

There are three farmability criteria for the COMIDA2-based food-chain model based on the parameters DOSEMILK, DOSEOTHR, and DOSELONG. DOSEMILK and DOSEOTHR define the maximum allowable food ingestion dose from milk crops and non-milk crops, respectively, during the first year after the accident. DOSELONG defines the long-term maximum allowable food ingestion dose for milk and non-milk crops combined (i.e., for years two through nine). These parameters are specified in terms of a maximum allowable individual dose (*Sv*) resulting from all food ingestion radionuclides. These three criteria are loosely equivalent to the input parameters $PSCMLK_i$, $PSCOTH_i$, and $GCMAXR_i$ of the original food-chain model; however, the original food-chain parameters are instead specified in terms of maximum permissible ground concentrations for each food ingestion radionuclide.

MACCS automatically triggers milk and non-milk crop disposal when either of the following conditions apply:

(1). when a farm area is not immediately habitable (i.e., habitation dose [Equation (3-17)] exceeds DSCRLT in the first year of the long-term phase), or

(2). when the second-year food ingestion dose [Equation (3-26)] exceeds the long-term food ingestion dose criterion (DOSELONG).

This is like the "coupled" option from the original MACCS food model. If neither DSCRLT or DOSELONG lead to the triggering of milk and non-milk crop disposal, MACCS individually evaluates milk and non-milk crops in the first year. If the milk dose exceeds DOSEMILK, milk disposal occurs, in which case there are no milk doses in the spatial element in the first year and there are milk disposal costs. If the non-milk dose exceeds DOSEOTHR, non-milk disposal occurs, in which case there are no non-milk doses in the spatial element in the first year and there are non-milk crop disposal costs.

MACCS also evaluates the need for farm interdiction each year after the accident. For any year that farm interdiction occurs, no food ingestion doses occur. Just as with the original food-chain model, the farmland interdiction applies to *all* crop categories; there is no provision for long-term interdiction of a subset of the crops.

For any year that farm interdiction occurs, farm interdiction costs occur for that year, unless the farm area is condemned in which case the full value of the farm area is a loss. Just as the original food model, the COMIDA2 food model evaluates up to nine years of farmland interdiction. In either model, if farmland is still not farmable in the ninth year of evaluation, the farmland is permanently condemned. As such, the maximum period of *temporary* farmland interdiction is eight years.

The COMIDA2 food-chain model triggers farm interdiction in the following periods and conditions:

(1). in every year the farm area is not habitable (i.e., habitation dose in the long-term phase [Equation (3-17)] exceeds DSCRLT),

(2). in the first year, when the non-milk crop requires disposal (i.e., when the first year non-milk dose [Equation (3-28)] exceeds DOSEOTHR),

(3). in the first year, when the second-year food ingestion dose [Equation (3-26)] exceeds the long-term food ingestion dose criterion (DOSELONG), and

(4). after the first year, in every year the annual food ingestion dose [Equation (3-26)] exceeds the long-term food ingestion dose criterion (DOSELONG).

As discussed in condition (1), habitability restrictions cause farm interdiction each year that habitability is restricted. In condition (2), non-milk crop disposal also triggers farm interdiction, but only in the first year. This is like the “coupled” option from the original MACCS food model, except that milk crop disposal does not affect farm interdiction in the COMIDA2 food model.

While MACCS does not evaluate DOSELONG in the first year, MACCS still triggers farm interdiction in the first year when the second-year dose exceeds DOSELONG, as shown in condition (3). The model assumes that the food doses resulting from successive years of production do not increase with time. Therefore, once criteria no longer require farm interdiction, farm production for that year and all subsequent years is allowed.

5 SOCIOECONOMIC IMPACTS AND COSTS

Like other types of disasters, nuclear accident impacts can be divided into two categories, market and nonmarket (National Academy of Sciences / National Research Council, 2004; Organisations for Economic Co-operation and Development [OECD], 2006). Market impacts (sometimes called "financial impacts" or "special damages") of a nuclear accident include onsite and offsite property damage, economic disruptions, various accident-related expenditures, and nuclear industry impact. Nonmarket impacts (sometimes called "noneconomic impacts" or "general damages") include health effects, environmental damage, and societal disruptions. Nosek (2018, pp. 64-92) provides a conceptual overview of the market and nonmarket impacts important to the cost assessment of nuclear accidents.

The MACCS cost models consider the following losses:

- Daily costs incurred during temporary evacuation and relocation,
- One-time relocation costs resulting from temporary interdiction or permanent condemnation,
- Decontamination costs to remediate habitation restrictions,
- The combined cost of depreciation and loss of use of temporarily interdicted property,
- The value of property that is permanently condemned, and
- Economic losses resulting from crop disposal.

MACCS does not produce an exhaustive set of nuclear accident costs. Because MACCS is an offsite consequence code, MACCS does not evaluate the onsite damages or economic disruptions of the nuclear plant. Other market costs not considered include housing market impacts on property values, decontamination in habitable areas, removal of condemned structures, cost of litigation and a compensation system, medical expenses, and impacts on tourism, trade, and the commercial nuclear power industry from stigma effects. Additionally, the MACCS cost models do not estimate an economic value for nonmarket impacts. As such, the cost models do not consider the cost of health effects, environmental damage, or the burden of societal disruptions. However, MACCS does evaluate important metrics related to these categories, including the number of cancer fatalities and other health effects, the number of displaced individuals, and the amount of land contamination. For a comprehensive cost assessment, users can consider evaluating these other types of nuclear accident costs outside of MACCS. The cost model outputs and metrics related to displaced populations and land contamination are discussed in Section 5.4, and radiation-induced health effect outputs are discussed in Section 6.3.

All the cost estimates modeled in MACCS are triggered based on a protective action. The protective action models are discussed in more detail in Section 4. Supporting economic and demographic data associated with the accident site are supplied in the site data file. Evacuation and early relocation contribute to the daily costs in the early phase, and intermediate phase relocation contributes to the daily costs in the intermediate phase. These costs accumulate with time and depend on how long the protective action exists. Section 5.1 and 5.2 discuss these costs in more detail.

Most of the calculated costs are attributed to the long-term phase, as they are based on the long-term habitability and farmability criteria. The long-term relocation cost, decontamination costs, condemnation costs, and crop disposal costs are all one-time costs, while the combined cost of depreciation and loss of use is a cost that accumulates with time.

Like protective actions, costs are divided into farm and non-farm areas. All the cost estimates have a unit cost aspect to them, where farm costs are based on a per hectare of farmland and non-farm costs have a per capita basis.

The unit cost of evacuation, relocation, and decontamination are user inputs. The unit cost of decontamination in farm and non-farm areas is particularly difficult for users to accurately predict and tends to be more expensive than expected. One reason for this is that farm and non-farm areas are broad categories of land use. Non-farm areas in particular are not just one type of land use, but rather a combination of many types of land use that include everything from uninhabited forest areas to downtown metropolitan areas. Since MACCS does not model these individual land use types, it is up to the user to include all the decontamination-related activities within these areas in sufficient detail and realism in order to provide MACCS decontamination costs and dose reduction factors that properly reflect the average land use. Another reason these values are difficult to predict is that the U.S. does not have a set of decontamination policies for different land-uses and instead plans to develop such policies post-accident. This complication makes it difficult for the user to know how to best model decontamination in these areas. Users should compare their decontamination costs against past decontamination experience to determine whether their results compare favorably, and to understand what level of uncertainty might exist.

MACCS indirectly accounts for income in the property losses by treating tangible property as an asset and using an expected rate of return on this asset. When property is unusable for a period, MACCS assumes that the property becomes less valuable because it cannot generate a return. In this way, MACCS models the combined long-term costs from loss-of-use and unmaintained depreciation as a decrease in the value of property. Because the property value cannot become less than zero, this creates a fundamental constraint that the combined loss-of-use and depreciation cannot exceed the original property value. It should be noted that the losses are not truly coupled, and they can exceed the original property value when the losses are large enough. As an alternative to the loss-of-use model, the user can instead choose to capture income losses from individuals and businesses as part of the relocation costs and set the discount rate to a value of zero.

MACCS models crop disposal costs as an economic loss equal to the sale of milk and non-milk products from farm areas. Crop disposal was originally developed as a protective action against doses of the current growing season pathways, which is part of the original MACCS food-chain model. The COMIDA2 food-chain model does not distinguish between long-term ingestion doses and doses from the current growing season. However, the concept that farmers would face an immediate, one-time economic loss when they are not allowed to sell their current crops still holds true. For this reason, and to maintain consistency between the two food-chain models, both include crop disposal costs.

5.1 Early Phase Costs

The costs resulting from early protective actions of the early phase are calculated for evacuation and early relocation. The occurrence of evacuation and early relocation are based on the protective action models discussed in Section 4.2.1 and Section 4.2.2, respectively. If neither evacuation nor early relocation begin before the end of the early phase, there is no early phase cost. MACCS does not model costs associated with KI ingestion or sheltering.

Evacuation of cohort *i* only occurs inside the evacuation and sheltering boundary $NUMEVA_i$, and early relocation of cohort *i* only occurs outside this boundary. Because $NUMEVA_i$ can vary between cohorts, it is possible for a spatial element to have evacuation costs for one cohort and early relocation costs for another cohort. The total cost of early protective actions CE in a spatial element is the sum of the protective action costs CE_i for each cohort *i*, where the protective action can be either evacuation or early relocation.

$$CE = \sum_i CE_i \tag{5-1}$$

In a spatial element, the cost of the early protective action CE_i for cohort *i* (for either evacuation or early relocation) is the following:

$$CE_i = CEV \cdot \Delta t_i \cdot POP_i \tag{5-2}$$

Where

- CE_i is the early protective action cost (*$*) for cohort *i*,
- CEV is the daily per capita cost (*$/person-day*), as specified by the parameter EVACST,
- Δt_i is the duration (*days*) of the protective action for cohort *i* discussed below, and
- POP_i is the population of cohort *i*.

The model defines the population of cohort i residing within a spatial element according to the cohort modeling option chosen by the user. This is discussed in more detail in Section 1.3.

In MACCS, the duration of evacuation is the period starting when evacuation begins to the end of the early phase ENDEMP. The evacuation timeline is discussed in Section 0. The early relocation duration is the period starting when early relocation begins to the end of the early phase. There are two types of early relocation, each with different timelines, which are discussed in Section 4.2.2.

EVACST ($/person-day) can include the cost of temporary lodging, meals, transportation, and lost income for an individual during the early phase or reflect other early phase costs the user deems appropriate.

5.2 Intermediate Phase Costs

After the early phase ends, relocation costs during the intermediate phase are based on the RELCST parameter and the number of displaced individuals during the intermediate phase. RELCST is a daily cost like EVACST in the early phase. MACCS calculates relocation during the intermediate phase based on the intermediate phase habitation restrictions and is not based on the early phase evacuation or early relocation models. As such, the number of displaced individuals during the intermediate phase is almost certainly different than those during the early phase, potentially significantly different depending on the source term and modeling values chosen for the different phases.

Modeling the intermediate phase is optional for the user. If there is no intermediate phase, MACCS does not calculate any daily costs for displaced individuals after the early phase. Users can choose to capture daily costs after the early phase by incorporating them as a lump sum cost in the parameter POPCST, which is a one-time relocation cost during the long-term phase.

Other costs associated with loss of use and depreciation occur during the period of the intermediate phase; however, MACCS calculates the extent of these costs based on long-term habitation and farming restrictions. For this reason, these costs are included in the long-term phase costs.

The cost of intermediate phase relocation in a spatial element is the following:

$$CI = CIR \cdot \Delta t \cdot POP \quad \textbf{(5-3)}$$

Where

- CI is the cost of intermediate phase relocation (*$*),
- CIR is the daily cost (*$/person-day*) of intermediate phase relocation per individual, as specified by the parameter RELCST,
- Δt is the duration (*days*) of intermediate phase relocation period, and
- POP is the displaced population (*persons*) of a spatial element due to intermediate phase habitation restrictions.

For the intermediate phase, MACCS evaluates habitation restrictions at the beginning of the period. When habitation is restricted, it is restricted for the entire period of the intermediate phase. Therefore, the duration of relocation, Δt, is either the full duration of the intermediate phase, DUR_INTPHAS, or zero.

Like the daily costs in the early phase, RELCST can include the daily cost incurred for providing temporary lodging, meals, transportation, and lost income for an individual during the intermediate phase or reflect other intermediate phase costs the user deems appropriate.

5.3 Long-Term Phase Costs

The costs from the long-term phase are those associated with long-term protective actions. These costs depend on the severity and extent of contamination, the time of year when the accident occurs, the site of the accident (the land area and population impacted), and the duration of the protective actions.

MACCS calculates long-term protective action costs for each spatial element. These costs are divided into two groups, farm costs and non-farm costs. MACCS calculates farm costs based on the area of restricted farmland (*$/hectares*). Non-farm costs are calculated on a per capita basis (*$/person*), according to the number of displaced individuals. Non-farm property includes residential, commercial, and public land, improvements, equipment, and tangible possessions.

In a spatial element, the cost of long-term protective actions is determined in the following way:

$$CL = C^{NF} \cdot POP + C^{F} \cdot AF \qquad \textbf{(5-4)}$$

Where

- *CL* is the total cost incurred as a result of long-term protective action taken within a given spatial element (*$*),
- C^{NF} is the per capita cost (*$/person*) of long-term protective actions in a non-farm area,
- *POP* is the displaced population (*persons*) from a spatial element due to long-term habitation restrictions,
- C^{F} is the unit cost (*$/hectare*) of long-term protective actions in a farm area, and
- *AF* is the size of the restricted farm area (*hectares*) in the spatial element.

The population within a spatial element, *POP*, is user-specified and the farmland area within the spatial element, *AF*, is calculated by MACCS using the geometric grid input data and site data.

The per capita cost of long-term protective action for non-farm areas, C^{NF}, is either the cost of restoring habitability or the cost of condemning the non-farm area when it is not possible or cost effective to restore habitability. C^{NF} is discussed in more detail in the next section.

The unit cost of long-term protective action for farm areas, C^{F}, is the sum of (1) the unit cost of restoring habitability and farm production or the unit cost of condemning the farm area and (2) if applicable, the unit cost of disposal of growing season crops. These are discussed in more detail in the Section 5.3.2.

5.3.1 Costs in Non-farm Areas

MACCS enforces habitation restrictions in a spatial element when groundshine and resuspension inhalation doses exceed the long-term habitability criterion. In the non-farm area of the spatial element, MACCS then requires decontamination, decontamination with additional temporary interdiction, or permanent condemnation. MACCS assumes that non-farm areas are condemned when very contaminated areas cannot be restored to habitability within 30 years, or when condemnation is more cost effective than decontamination. The protective action models in Section 4.4 discuss this in more detail.

The cost models for areas with temporary restrictions are different than areas with permanent condemnation. When a non-farm area is subject to temporary restrictions, the unit cost in the non-farm area portion of the spatial element is the following:

$$C^{NF} = CD_{\ell}^{NF} + CC^{NF} + CF \tag{5-5}$$

Where

- C^{NF} is the per capita cost *($/person*) of restoring habitability in the non-farm area,
- CD_{ℓ}^{NF} is the per capita decontamination cost of the minimum decontamination level ℓ that can restore habitability in non-farm areas (*$/person*), as specified by the parameter CDNFRM$_{\ell}$,
- CC^{NF} is the combined costs from loss-of-use and depreciation for the non-farm area (*$/person*), as defined below, and
- CF is the one-time per capita cost (*$/person*) to relocate individuals and businesses in the long-term phase as discussed below, given by the parameter POPCST.

The one-time per capita long-term relocation cost, CF, is per displaced individual. As such, it is only applicable to non-farm areas. For individuals, POPCST can include various relocation expenses including moving costs, replacement of lost household items, and expenses for replacement housing. Since the duration of the early phase (and intermediate phase, if applicable) may not be long enough to cover the full period of temporary housing until a displaced family can either move back or find permanent residence elsewhere, the user may choose to capture the remainder of these costs as a lump sum in the value of POPCST. For businesses, POPCST can include moving costs, operating expenses during a transitional period, renting a temporary place of business, office supplies, and other expenses. POPCST can also account for personal and business income losses for a transitional period until businesses and individuals can reestablish their income.

The per capita decontamination costs for non-farm areas CD_{ℓ}^{NF} are specified by the user for each level of decontamination effort ℓ defined in the protective actions. Decontamination costs depend on the types of contaminated surfaces and decontamination methods used throughout the modeling domain. Since MACCS does not model at the level of decontamination methods required for a range of land uses, it is up to the user to model decontamination within these areas and to give MACCS decontamination costs and dose reduction factors that properly reflect the average land use, while also considering waste storage, transportation, and disposal costs.

MACCS models the combined long-term costs from loss-of-use and unmaintained depreciation CC^{NF} as a decrease in the value of property. The post-accident property value is first estimated based on a present value calculation. Unmaintained depreciation is the decrease in the value of land improvements over time. MACCS assumes that land improvements depreciate faster than normal without maintenance according to a continuously compounding depreciation rate. Loss of use is the loss of return that the property would generate compared with normal use. Even if property is not an investment, there is an opportunity cost of holding property that does not generate a return. Under other circumstances, the property could be sold, and the proceeds invested, which in turn would generate a return. One method to value an asset is to use a discounted cash flow evaluation. As such, MACCS treats property as an asset and uses a discount rate to calculate the present value over an interdiction period.

The present value calculation considers both the interruption of use and maintenance of the property for a certain period. MACCS calculates the present value of non-farm property PV^{NF} in a spatial element after an accident using the following equation:

$$PV^{NF} = e^{-rt} \cdot [(1 - a^{NF}) + a^{NF} \cdot e^{-dt}] \cdot VW^{NF} \tag{5-6}$$

Where

- VW^{NF} is the per capita value *($/person*) of wealth in the non-farm area (includes the cost of the land, buildings, infrastructures, equipment, and other tangible assets) before the accident as specified in the site file (or given by VALWNF when there is no site file),
- a^{NF} is the regional fraction of wealth (unitless) for non-farm areas that is from land improvements (e.g., buildings), given by the parameter FRNFIM,
- d is the depreciation rate (yr^{-1}) of property improvements (e.g., buildings) from a lack of habitation and maintenance, given by the parameter DPRATE,
- r is a rate of return (yr^{-1}), given by the parameter DSRATE, and
- t is the interdiction period (*yr*) caused by habitation restrictions in the spatial element.

When the user chooses to use a site data file, the property value before the accident VW^{NF} is specified in the site data file. Otherwise, VW^{NF} is given by the parameter VALWNF. Non-farmland wealth includes all public and private property not associated with farming, that would be unusable if the region was temporarily interdicted or permanently condemned. Although the term ‘wealth’ may seem to imply the value of stocks, bonds, or other financial interests, these are not included in the definition of this parameter. In this context, wealth is real estate and other tangible property.

The parameter, r, is a discount rate to account for a rate of return on property investment. The definition of r has evolved slightly over time. In the Reactor Safety Study (NRC, 1975), r in Equation (5-6) represented the interest rate plus the tax rate. The original MACCS Model Description (NRC, 1990) defines r to be the inflation adjusted rate of investment return, and the current draft MACCS User’s Guide (SAND-2021-1588) defines it to be the expected rate of return from land, buildings, equipment, etc.

In Equation (5-6), the unmaintained depreciation rate d and the loss-of-use discount rate r both decrease the present value of the non-farm property according to exponential functions. As such, r and d are continuous compounding rates, not annual compounding rates. (Note, the user can convert an annually compounded rate r_a to a continuously compounded rate r using the equation $r = ln[1 + r_a]$.) The rate of unmaintained depreciation d only affects the value of land improvements and not land itself, while the discount rate r affects both. MACCS can then estimate the property loss due to temporary interdiction, CC^{NF}, by subtracting the value after the accident from the value before the accident.

$$CC^{NF} = VW^{NF} - PV^{NF} \tag{5-7}$$

Substituting Equation (5-6) into Equation (5-7) and rearranging the expression gives the following:

$$CC^{NF} = \{1 - e^{-rt} \cdot [(1 - \mathrm{a}^{NF}) + \mathrm{a}^{NF} \cdot e^{-dt}]\} \cdot VW^{NF} \tag{5-8}$$

Where all terms are previously defined. Note that this expression does not directly consider the impact of contamination on property values. Properties in contaminated areas may not have utilities, and the local community may not have jobs or functional services (e.g., schools, hospitals, grocery stores, a functional local government). Also note that a fundamental constraint of this equation is that the combined losses in this expression is based on the original property and cannot exceed this value. Actual losses from depreciation and loss-of-use are not coupled in this manner and can exceed the property value, especially when an event causes property loss, income loss, and additional expenses.

When a non-farm area is subject to permanent condemnation, the unit cost in the non-farm area is the following:

$$C^{NF} = VW^{NF} + CF \tag{5-9}$$

Where

- C^{NF} is the per capita cost (*$/person*) of a condemned non-farm area, and
- VW^{NF} and CF are previously defined.

In MACCS, the per capita condemnation losses include the full property loss in the non-farm area VW^{NF} and the relocation costs CF.

In contrast to the current model, condemnation losses normally include both property loss and income loss, and therefore losses can exceed the value of the property. For example, if a business or a household is immediately compensated for the full value of their lost property, there is still an income interruption period. This is a transitional period that ends when business operation and employment activity are reestablished. Thus, the compensation of property loss, income loss, and relocation costs are all necessary to be made whole.

In the temporary interdiction costs discussed above, the combined cost from loss-of-use and depreciation is constrained by the property value. However, the fact that condemnation losses can exceed property loss also indicates that the maximum temporary interdiction losses should exceed property loss as well and for the same reason. Alternatively, the user can capture all income losses fully in the per capita relocation costs and omit them from Equation (5-8) and (5-11) (i.e., use a discount rate r of zero). This assumes that the income loss is the same for interdiction and condemnation, which may not be the case.

5.3.2 Costs in Farm Areas

MACCS assumes that the farm area portion of a spatial element needs to be both habitable and farmable in order to perform farming activity. The number of years a farm area is interdicted (due to either habitation or long-term farming restrictions) affects the cost of interdiction.

Habitation restrictions occur when groundshine and resuspension inhalation doses exceed the long-term habitability criterion. When there are habitation restrictions, MACCS then requires decontamination, decontamination with additional temporary interdiction, or permanent condemnation. This is the same as the non-farm area.

Farming restrictions occur in farm areas when levels exceed the farmability criteria. The farmability criteria depend on which of the two food-chain models is used, which are discussed in more detail in Section 3.4.3 and 4.4.2. For long-term farming restrictions, MACCS requires either temporary interdiction or permanent condemnation. MACCS does not require decontamination from farming restrictions alone.

The cost models for farm areas with temporary restrictions are different than areas with permanent condemnation. MACCS assumes that farm areas are condemned when very contaminated areas cannot be restored by the beginning of the ninth year, or when condemnation is more cost effective than decontamination. MACCS also assumes that farm areas are condemned when farming restrictions are still required at the beginning of the nineth year.

When a farm area is subject to temporary restrictions, the unit cost in the farm area of a spatial element is the following:

$$C^F = CD_\ell^F + CC^F + CMD + CNMD \tag{5-10}$$

Where

- C^F is the unit cost (*$/hectare*) of restoring habitability and farm production in the farm area portion of the spatial element,
- CD_ℓ^F is the unit decontamination costs (*$*) of the minimum decontamination level ℓ that can restore habitability in farm areas (*$/hectare*), as specified by the parameter CDFRM_ℓ,
- CC^F is the combined costs (*$/hectare*) from loss of use and depreciation for farm areas,
- CMD is the unit cost of milk disposal (*$/hectare*) as discussed below, and
- $CNMD$ is the unit cost of non-milk disposal (*$/hectare*) as discussed below.

MACCS assumes that farm areas are unoccupied and assigns all relocation costs to non-farm areas on a per capita basis.

The unit decontamination cost in farm areas CD_{ℓ}^{F} only applies when there is farm decontamination. MACCS assumes farm decontamination only occurs to restore habitability and not farmability. If there are no habitation restrictions or if the farm area is condemned, there are no decontamination costs. This is discussed more in Section 4.4.2.

The combined costs from loss of use and depreciation for farm areas CC^{F} in a given spatial element is the following:

$$CC^{F} = \{1 - e^{-rt} \cdot [(1 - \mathrm{a}^{F}) + \mathrm{a}^{F} \cdot e^{-dt}]\} \cdot VW^{F} \qquad \textbf{(5-11)}$$

Where

- VW^{F} is the unit value *($/hectare*) of wealth in farm areas (includes the cost of the land, buildings, infrastructure, equipment, and other tangible assets) before the accident as specified in the site file (or given by VALWNF when there is no site file),
- a^{F} is the fraction of the wealth (unitless) for farm areas that is from land improvement and other tangible assets (i.e., not land), given by the parameter FRFIM,
- d is the depreciation rate (yr^{-1}) of property improvements from a lack maintenance, given by the parameter DPRATE,
- r is the rate of return on investment (yr^{-1}), given by the parameter DSRATE, and
- t is the interdiction period (*yr*) caused by either habitation or farming restrictions in the spatial element, whichever is longer.

This expression is the same as Equation (5-8) except it uses values for farm areas. See the discussion of Equation (5-8) for more details.

In MACCS, the unit cost of milk disposal CMD and non-milk disposal $CNMD$ only apply when the protective action model requires these actions. Milk and non-milk disposal are one-time actions and refer to the disposal of crops the farmer began growing before the accident. These actions can occur in farm areas without habitability or long-term farming restrictions. Either food-chain model can trigger crop disposal, although crop disposal can only occur when the accident occurs during the growing season when using the original MACCS food model. Crop disposal is discussed in more detail in Section 4.4.2.

When crop disposal occurs, there is an economic loss since farmers cannot sell the milk and non-milk products of these crops. When non-milk disposal occurs, MACCS assumes that the unit cost is equal to the fraction of the annual farm production that comes from non-dairy crops. When milk disposal occurs, MACCS assumes that the unit cost is equal to the value of three months of dairy production. This assumes that contamination of pasture and feed crops being grown for dairy cows would cause an interruption of dairy sales that is roughly equal to one-quarter of a year, and that stored feed could be used to help reduce the overall impact.

Both food-chain models use the same equations to determine the unit costs. The unit cost of milk disposal (*$/hectare*) within any spatial element, CMD, is calculated as follows:

$$CMD = FP \cdot FDP \cdot FMD \tag{5-12}$$

Where

- FP is the average annual farm production value (*$/hectare*),
- FDP is the fraction of annual farm production value (dimensionless) that comes from dairy farm production, and
- FMD is the fraction of the year (dimensionless) for which milk disposal occurs.

The values of *FP* and *FDP* are user-supplied input data. This information is given in the site data file, or from the parameters FRMPRD and DPFRCT, respectively, when no site data file is used. The value of *FMD* is fixed in the code and is equal to 0.25, that is, milk disposal occurs for three months of a year.

The unit cost of disposal of non-milk crops (*$/hectare*) in a spatial element, $CNMD$, is calculated as follows:

$$CNMD = FP \cdot (1 - FDP) \cdot FNMD \tag{5-13}$$

Where

- $FNMD$ is the fraction of the year (dimensionless) for which non-milk crop disposal occurs, and
- FP and FDP are described above in Equation (5-12).

The value of $(1 - FDP)$ represents the fraction of annual farm production which comes from non-dairy crops. The value of *FNMD* is fixed in the code and is equal to 1, that is, non-milk disposal occurs for a full year.

When a farm area is subject to permanent condemnation, the unit cost in the farm area of a spatial element is the following:

$$C^F = VW^F + CMD + CNMD \tag{5-14}$$

Where

- C^F is the unit cost (*$/hectare*) of condemnation in the farm area portion of the spatial element, and
- VW^F, CMD, and $CNMD$ are the same as previously defined.

The condemnation costs in farm areas are like the condemnation costs in non-farm areas in that they are largely based on the value of wealth in the spatial element. However, farm area costs include crop disposal costs and non-farm areas include the per capita relocation costs, and these additional costs are reflected in the condemnation costs of the respective areas.

5.4 Socioeconomic Impact and Cost Model Outputs

MACCS reports five output categories related to socioeconomic impacts and costs. Many of the outputs could overlap as outputs of protective action modeling. However, they are included here to highlight the fact that many of the consequences of protective actions (such as displaced individuals) are important indicators to the societal impact of the accident. Table 5-1 gives a breakdown of each output category:

Table 5-1 Socioeconomic Impact and Cost Output Category Breakdown by Module

Result Type	EARLY	CHRONC	Cohort-specific Results	Method of Combining Cohorts
Type E: Population Movement Across Radius	X		Yes	Sum
Type 10: Economic Cost Measures		X	No	Sum
Type 11: Maximum Distance for Protective Actions		X	No	N/A
Type 12: Impacted Area / Population		X	No	N/A
Type 14: Evacuated and Relocated Population		X	No	Sum

Most outputs discussed in this section are results generated from the CHRONC module, reflecting results gathered from all accident phases. The exception to this is the is Type E output, “Population Movement Across Radius.” While this output is not as strong an indicator of societal impact as other outputs, it is discussed here given its similarity to other population-related outputs.

There are no outputs discussed here that are generated directly by both the EARLY and CHRONC modules. Nevertheless, Type 10 and 14 outputs are CHRONC results that gather information from all accident phases (i.e., early, intermediate, and long-term phases) to generate results. MACCS does not report the associated early phase results of these outputs unless CHRONC is included in the analysis.

Type E Results: Population Movement Across Radius

The Type E output reports the fraction of each cohort that transit outward across the outer radial distance of a user-specified radial interval at user-specified time intervals. MACCS does not model the transit of individuals that are displaced by early relocation.

The output does not report results in time intervals with no changes. The output only considers the first crossing. (Evacuees in a network evacuation model can cross a boundary more than once.)

Type 10 Results: Economic Cost Measures

The Type 10 output reports the cost estimates in dollars of the various cost categories evaluated in MACCS for a region of interest. The user defines the region of interest by specifying two radial intervals that define the range of the region. Results are only available when using a food ingestion pathway (FDPATH = “OLD” or “NEW”).

Note that while all the cost categories that MACCS evaluates are anticipated types of costs from an accident, the set of costs is not exhaustive. Nosek (2018, pp. 64-92) provides a conceptual overview of the market and nonmarket impacts important to the cost assessment of nuclear accidents.

All of the cost estimates considered in MACCS are triggered based on a protective action. The cost models divide costs into farm and non-farm area costs, where early and intermediate phase costs are included with the non-farm area costs. The derivation for the farm area costs in a spatial element are in units of *dollars per hectare* (*$/ha*), and the derivation for the non-farm area costs in a spatial element are in units of *dollars per capita* (*$/capita*). To obtain a cost value, the cost models multiply the farm results (*$/ha*) and non-farm results (*$/capita*) by the farm area AF_n (*ha*) and displaced population POP_n (*capita*) for spatial element *n*, respectively, and then summed across all spatial elements in the region of interest. The farm area and population values affected by protective actions and used as input to these calculations are reported in the Type 12 output. MACCS calculates early phase costs for each cohort, although only reports the sum of these in the output. Table 5-2 gives a breakdown of each cost output category.

Table 5-2 Economic Cost Measures

Output Name	Description	Derivation
TOTAL ECONOMIC COSTS	The total sum of the cost model outputs	Sum all farm and non-farm area costs
POP.-DEPENDENT COSTS	The sum of the non-farm cost model outputs	Sum of all non-farm area costs below, including the early and intermediate phase costs.
FARM-DEPENDENT COSTS	The sum of the farm cost model outputs	Sum of all farm area costs below.
POP.-DEPENDENT DECONTAMINATION COST	The decontamination costs in non-farm areas	CDNFRM, multiplied by the population
FARM-DEPENDENT DECONTAMINATION COST	The decontamination cost in farm areas	CDFRM, multiplied by the farm area
POP.-DEPENDENT INTERDICTION COST	The combined loss of use and depreciation costs in non-farm areas	Equation (5-8), multiplied by the population
FARM-DEPENDENT INTERDICTION COST	The combined loss of use and depreciation costs in farm areas	Equation (5-11), multiplied by the farm area
POP.-DEPENDENT CONDEMNATION COST	The lost wealth and long-term relocation costs in non-farm areas	Equation (5-9), multiplied by the population
FARM-DEPENDENT CONDEMNATION COST	The lost wealth in farm areas	VW^F as defined in Equation (5-14), multiplied by the farm area
EMERGENCY PHASE COST	The sum of the evacuation and early relocation costs over the set of cohorts	Equation (5-2), summed over all cohorts
INTERMEDIATE PHASE COST	The intermediate phase relocation costs	Equation (5-3)
MILK DISPOSAL COST	The economic loss of milk sales due to crop disposal	Equation (5-12), multiplied by the farm area
CROP DISPOSAL COST	The economic loss of non-milk sales due to crop disposal	Equation (5-13), multiplied by the farm area

Type 11 Results: Maximum Distance for Protective Actions

The Type 11 output is the farthest distances (*km*) that long-term protective actions occur in each weather simulation. Results are only available when using a food ingestion pathway (FDPATH = "OLD" or "NEW").

Long-term protective actions occur when a dose (or concentration) exceeds a user-specified dose (or concentration) threshold. The protective action models in Section 4.4 discuss the decision process for determining when a long-term protective action occurs in more detail. The long-term protective actions reported in the Type 11 output are shown in Table 5-3.

Table 5-3 Maximum Distance for Protective Actions Outputs

Output Name	Description
FARM-DEPENDENT DECONTAMINATION DIST.	The maximum distance farm areas are subject to decontamination.
POP.-DEPENDENT DECONTAMINATION DIST.	The maximum distance non-farm areas are subject to decontamination.
FARM-DEPENDENT INTERDICTION DIST.	The maximum distance farm areas are subject to temporary long-term habitation and/or farming restrictions.
POP.-DEPENDENT INTERDICTION DIST.	The maximum distance non-farm areas are subject to temporary long-term habitation restrictions.
FARM-DEPENDENT CONDEMNATION DIST.	The maximum distance farm areas are subject to permanent condemnation.
POP.-DEPENDENT CONDEMNATION DIST.	The maximum distance non-farm areas are subject to permanent condemnation.
MILK DISPOSAL DIST.	The maximum distance farm areas are subject to milk disposal.
CROP DISPOSAL DIST.	The maximum distance farm areas are subject to crop disposal.

Type 12 Results: Impacted Area / Population

This output category reports the farm area (*ha*), non-farm area (*ha*), and population impacted by long-term protective actions for a region of interest. The user defines the region of interest by specifying two radial intervals that define the range of the region. Results are only available when using a food ingestion pathway (FDPATH = "OLD" or "NEW").

In the output names, "POP." is short for population and refers to the non-farm portion of the region and "FARM" refers to the farm portion. Because the period of decontamination is also a period of interdiction, the non-farm decontamination and temporary interdiction values are always the same, making these redundant. Likewise, the farm decontamination area is the same as the farm area subject to habitation restrictions, but the latter is not reported. Table 5-4 gives a breakdown of the different impacted areas and populations reported in the Type 12 output.

Table 5-4 Impacted Area / Population Outputs

Output Name	Description
FARM DECONTAMINATION (ha)	The farm area subject to decontamination
POP. DECONTAMINATION (INDIVIDUALS)	The population from non-farm areas subject to decontamination
POP. DECONTAMINATION AREA (ha)	The non-farm area subject to decontamination
FARM INTERDICTION (ha)	The farm area subject to temporary long-term habitation and/or farming restrictions
POP. INTERDICTION (INDIVIDUALS)	The population from non-farm areas subject to temporary long-term habitation restrictions
POP. INTERDICTION AREA (ha)	The non-farm area subject to temporary habitation restrictions
FARM CONDEMNATION (ha)	The farm area subject to permanent condemnation
POP. CONDEMNATION (INDIVIDUALS)	The population from non-farm areas subject to permanent condemnation
POP. CONDEMNATION AREA (ha)	The non-farm area subject to permanent condemnation
MILK DISPOSAL AREA (ha)	The farm area subject to milk disposal
CROP DISPOSAL AREA (ha)	The farm area subject to non-milk disposal

Type 14 Results: Evacuated and Relocated Population

This set of outputs gives a breakdown of the different types of displaced individuals according to the different protective actions for a region of interest. The user defines the region of interest by specifying two radial intervals that define the range of the region. Results are only available when using a food ingestion pathway (FDPATH = “OLD” or “NEW”).

This information can be helpful when determining the appropriate timing of early relocation, since a large population may take some time to fully relocate. The number of displaced individuals can also indicate the scale of societal burden caused by a nuclear accident.

Table 5-5 gives a breakdown of displaced individuals from different protective actions. If the project does not have an intermediate phase or does not use all 3 decontamination levels, these items do not appear in the output.

Table 5-5 Evacuated and Relocated Population Outputs

Output Name	Description
EVACUEES NOT AFFECTED BY PLUME	The displaced population from an evacuation area not downwind of a plume segment release and therefore were not at risk.
EVACUEES AFFECTED BY PLUME	The displaced population from an evacuation area downwind of a plume segment release.
NORMAL EMERGENCY PHASE RELOCATION	The displaced population from an early relocation area where the less urgent "normal" relocation is required.
HOTSPOT EMERGENCY PHASE RELOCATION	The displaced population from an early relocation area where the more urgent "hotspot" relocation is required.
INTERMEDIATE PHASE RELOCATION	The displaced population from an intermediate phase habitation restricted area.
LEVEL 1 DECONTAMINATION RELOCATION	The displaced population from a long-term habitation restricted area with light decontamination.
LEVEL 2 DECONTAMINATION RELOCATION	The displaced population from a long-term habitation restricted area with medium decontamination.
LEVEL 3 DECONTAMINATION RELOCATION	The displaced population from a long-term habitation restricted area with heavy decontamination.
DECONTAMINATION+INTERDICTION RELOC	The displaced population from a long-term habitation restricted area with heavy decontamination and an additional period of interdiction.
CONDEMNATION RELOCATION	The displaced population from a permanently condemned area.

6 RADIOGENIC HEALTH EFFECTS

Release of radioactive materials into the atmosphere during a severe reactor accident would cause downwind populations to be exposed to radiation. Both early fatalities and early injuries can occur in the exposed populations, if large enough exposures are delivered over a short enough period. Persons who survive large exposures or instead are exposed to small or moderate amounts of radiation may later contract other types of health effects, such as cancer.

Health effects from ionizing radiation are broadly categorized into two main categories, harmful tissue reactions and stochastic effects (i.e., cancer/heritable effects). Tissue reactions are "health effects that the severity of which varies with the dose and for which a threshold is believed to exist" (HPS, n.d.). Tissue reactions is also known as "deterministic" effects (and before that as "non-stochastic" effects). Tissue reactions is the preferred term as these effects can be altered after exposure by various biological response modifiers, i.e., they are not necessarily predetermined (ICRP, 2012).

Tissue reactions include acute effects that may lead to early fatalities (such as hematopoietic, pulmonary, and gastrointestinal syndromes) and early injuries (such as prodromal symptoms, erythema, pneumonitis, and thyroiditis). Early health effects from tissue reactions have a sparing effect when doses are protracted over time, meaning that doses spread over a longer period are less effective at causing the same biological effect. Tissue reactions also include late injuries and fatalities from degenerative conditions, including cataracts, cardiovascular disease, and cerebrovascular disease (ICRP, 2012; NASA, 2016). The sparing effect has not been observed in these late effects, meaning that fractionated and chronic doses may be important contributors to these effects. MACCS models for tissue reactions are designed for evaluating early effects that assume the sparing effect, and therefore may not be well suited to address late effects. Scientific understanding of how best to model late effects of tissue reactions is still developing.

Stochastic effects are health "effects that occur by chance and which may occur without a threshold level of dose, whose probability is proportional to the dose and whose severity is independent of the dose" (HPS, n.d.). These include cancers and heritable effects (also known as genetic effects). In practice, MACCS analyses do not typically model heritable effects, but MACCS is capable of modeling them assuming heritable risk coefficients are available.

MACCS quantifies two types of doses, those being (1) "acute doses" for estimating early health effects, and (2) "lifetime doses" for estimating stochastic health effects. The acute dose is equal to the applicable portion of the lifetime dose that contributes to early health effects, accounting for the sparing effect. The intent of the acute dose calculations is to estimate a dose level that when delivered entirely in one day is as effective at inducing acute health effects as the actual protracted dose. To estimate the acute dose, MACCS considers only early external doses and a time-weighted fraction of the early internal doses. Despite the potential length of the early phase, MACCS does not explicitly consider the sparing effect in the early external exposures. Thus, early external exposures are equivalent to an exposure that all occurs in a single day. In most cases, however, the sparing effect from early external exposures is small because emergency plans should ensure that no individuals are permitted to remain in a contaminated area for much longer than one day when dose levels are high enough to pose a risk of early health effects.

The lifetime dose is a dose from all phases and most exposure pathways that is used to calculate stochastic health effects. The stochastic health effects model uses individual doses to calculate individual cancer risks, and population doses to calculate the expected number of cancers and fatal cancers in a population. For the early phase, lifetime doses in MACCS include cloudshine, groundshine, direct inhalation, and resuspension inhalation, but not skin deposition. For the intermediate and long-term phases, the exposure pathways included in lifetime doses depend on whether they are used as individual doses (*Sv*) or population doses (*person-Sv*). Both individual and population doses include groundshine and resuspension inhalation. However, only population doses include food ingestion, water ingestion, and decontamination worker doses, making population doses and the associated number of health effects a more complete measure than individual risk. Individual doses do not include these other pathways because the individual residents within the spatial element where deposition occurs may not be the recipients impacted by these dose contributions.

MACCS can calculate cancer effects based on four different dose-response relationships. The annual-threshold and piecewise-linear dose-response relationships require annual doses, which are created by dividing the lifetime dose into annual periods. Acute, lifetime, and annual doses are weighted by RBE factors, which can be different for tissue reaction effects and stochastic effects. Acute doses, lifetime doses, and annual doses are discussed in more detail in Section 3.

MACCS typically models the early health effects and latent cancer health effects caused by radiation exposures in the population, using models originally described by Evans, Moeller, & Cooper (1985) and Evans (1990). Section 6.1 discusses the models for estimating the individual risk and expected number of early health effects, and Section 6.2 describes the models for estimating the individual risk and expected number of cancers.

Stochastic health effects like cancer are uncertain at low doses. MACCS has four options that allow users to evaluate different dose-response relationships at low doses and create upper and lower estimates. The four dose-response options are the following: LNT, linear quadratic, annual threshold, and piecewise linear. The LNT option tends to be the most common approach. Users should be aware that the name “linear no threshold” may be somewhat misleading. At low doses, risk from the LNT model in MACCS is adjusted downward by a DDREF. This factor is specifically designed to account for the understanding that small doses are less effective per unit dose than high doses in causing cancer. Therefore, this option may be better described as LNT adjusted by a DDREF, and it is only purely linear when DDREF is set to a value of one. Since the purpose of DDREF is to address low dose risk, DDREF provides users a way to evaluate low dose uncertainty. The use of LNT adjusted by a DDREF is an approach that is preferred or at least recognized by many cognizant bodies including ICRP (2005), National Council on Radiation Protection & Measurements (NCRP; 2001), National Academy of Sciences / National Research Council (2006), EPA (1999), and the United Nations Scientific Committee on the Effects of Atomic Radiation (2017). The German Commission on Radiological Protection (2014) preferred approach is LNT with no DDREF adjustment. NRCP (2018) found that most (but not all) recent epidemiological studies published in the previous ten years show excessive cancer effects at low dose and dose rates, and they conclude this shows additional support for the LNT hypothesis. This notably includes some larger studies finding excess cancer effects below 100 mGy.

The linear-quadratic option uses a quadratic response at low doses and linear relationship at high doses. The linear-quadratic dose response is also recognized by many of the same organizations and is very similar to the LNT adjusted by a DDREF. The annual-threshold model uses a dose truncation that excludes annual doses below a certain effective dose level. While most cognizant bodies do not support this approach, a notable exception is the French Academy of Sciences (2005), which rejects LNT and concludes that data suggests there is a practical threshold. ICRP states that while a threshold "does not seem unlikely" for certain types of cancer, "the evidence does not favour the existence of a universal threshold" (ICRP, 2005) and that the "possibility of a low-dose threshold for cancer risk is judged to be equivalent to that of an uncertain increase in the value of DDREF" (ICRP, 2007). The annual-threshold model may provide users with a convenient way to separate more certain health effects caused by relatively higher dose levels from less certain health effects from low doses. Finally, the piecewise-linear option is a tool that allows the user to design their own dose-response relationship for estimating health effects.

In MACCS, the annual-threshold option and the piecewise-linear option make low-dose adjustments twice, that is, with both DDREF and based on the annual effective dose thresholds. While this is potentially redundant, it is unlikely to have a significant effect unless organ doses are significantly nonuniform and assuming the user specifies similar threshold values for the DDREF and the effective dose threshold.

While very unlikely to be significant, it is mathematically possible to double count cancer fatalities. MACCS does not allow any cancer fatality risk to exceed 100% and does not allow any cancer fatalities to exceed the population. The risk model for early health effects does not allow double counting of early fatalities. In addition, MACCS reduces the total population in the intermediate and long-term phase by the number of early fatalities.

6.1 Early Health Effects Models

The fatalities and injuries that result from substantial radiation exposures incurred during short time periods (usually within weeks, though up to one year for pulmonary effects) are termed early health effects in MACCS.

The early health effect models calculate the individual risk of early health effects based on acute organ doses to individuals. MACCS then calculates the expected number of early health effects based on the individual risk. (This is different than the cancer models that instead calculate the expected number of cancers based on a population dose instead of an individual risk.)

The acute dose D_k that induces early health effect k is the sum of the doses from the early dose pathways to the target organ shown in Equation (3-8), using the inhalation dose coefficients that account for the sparing effect. The user tells MACCS which organ dose to use for each health effect by specifying the name of the organ dose (e.g., "A-STOMACH") in the parameter $ORGNAM_k$ of health effect k. For early health effects, the user should use the organ doses that begin with an "A-" as these are the acute organ doses calculated specifically for acute health effects. As discussed in Section 3, the acute organ dose is the absorbed dose weighted by the RBE for the type of radiation and (if applicable) weighted by the biological effect of a protracted dose on early health effects. These weightings are contained within the dose coefficients and are not part of the health effect calculations. (Note that because the absorbed dose is weighted by these factors, the doses are not truly in units of Gray, but rather some biological equivalent to the Gray. They are simply identified here as Gray since there is no official unit.)

The expected number of a specific early health effect N_k in the cohort of a spatial element is the average individual risk r_k of experiencing health effect *k* multiplied by the number of exposed people susceptible to the to the risk:

$$N_k = r_k \cdot f_k \cdot POP \quad \textbf{(6-1)}$$

Where

- POP is the population in a given cohort and spatial element,
- f_k is the fraction of the population that is susceptible to the risk of early health effect *k*, discussed below, and
- r_k is the risk of health effect *k* to an individual in a given cohort and spatial element.

For most early injuries, all individuals in an exposed population are susceptible to the injury (i.e., $f_k = 1$). However, early health effects to a fetus or to specific sex organs (e.g., sterility) would involve a certain fraction of the population. For early injuries, the population fraction f_k is given by the parameter EISUSC. For early fatalities, MACCS assumes that the full population is susceptible (i.e., $f_k = 1$).

The risks of early health effects r_k are sigmoid-shaped dose-response curves and depend on acute doses to the target organs in an exposed individual. Early health effects are expected to have a dose threshold. The risk distribution of the dose response reflects the distribution of different tolerances among the population, where the most sensitive persons react to a relatively lower dose and less sensitive persons can tolerate higher doses. In MACCS, the dose-response curves are cumulative hazard functions that have a Weibull distribution. The risk r_k of an early injury *k* to an individual in a given cohort and spatial element is as follows:

$$r_k = 1 - exp(-H_k) \quad \textbf{(6-2)}$$

Where H_k is the hazard function (dimensionless) that describes the dose-dependent rate that a given early health effect *k* occurs, which is described in more detail below. For early fatalities, MACCS does not calculate the individual risk from different causes. Instead, the risk of an early fatality r_{EF} to an individual in a given cohort and spatial element is based on the aggregated early fatality hazard H_{EF} from all causes:

$$r_{EF} = 1 - exp(-H_{EF}) \quad \textbf{(6-3)}$$

Where H_{EF} is the sum of the early fatality hazards from different causes, such as the impaired functioning of red (bone) marrow, the lungs, or the gastrointestinal tract (i.e., $H_{EF} = H_R + H_L + H_{GI}$). Since the user defines the early fatality hazards, more or fewer organs can be used. Calculating the aggregated early fatality risk using a simple aggregated early fatality hazard H_{EF} (instead of calculating them individually) avoids double counting that could occur if, for instance, an individual receives a lethal dose to both the lungs and red bone marrow. However, it neglects possible synergisms from impairment of multiple organs.

As recommended by Evans (1990), the hazard function H_k for a given cohort and spatial element is expressed as follows:

$$H_k(D_k) = \begin{cases} 0 & D_k < D_{T,k} \\ ln(2) \cdot \left(\frac{D_k}{D_{50,k}}\right)^{\beta_k} & D_k \geq D_{T,k} \end{cases} \quad \textbf{(6-4)}$$

Where

- D_k is the acute dose (Gy) to a target organ that induces early health effect k, discussed below,
- $D_{T,k}$ is the threshold dose (Gy) below which there is no early health effect k, discussed below,
- $D_{50,k}$ is the acute dose (Gy) that would induce early health effect k in half the exposed population, and
- β_k is the shape parameter (dimensionless) that determines the steepness of the sigmoid dose-response curve for early health effect k.

Equation (6-4) is for both early fatalities and early injuries, but they are defined by different parameters. The threshold dose $D_{T,k}$ is given by the parameter EITHRE_k for early injuries and EFFTHR_k for early fatalities. The median dose of induction $D_{50,k}$ is given by the parameters EIFACA_k for early injuries and EFFACA_k for early fatalities. (For early fatalities, this is sometimes referred to as the LD_{50}). The shape parameter β_k is given by the parameters EIFACB_k for early injuries and EFFACB_k for early fatalities.

MACCS Equation (6-4) is a piecewise function that explicitly accounts for a dose threshold. While early health effects are not expected to have a cutoff like this, they are observed to have a dose threshold greater than zero. Because the cumulative Weibull distribution implemented in MACCS does not have a dose threshold, an explicit dose threshold is necessary to be consistent with clinical observations.

When the shape parameter β_k is equal to one, the hazard function is linear. A value greater than one increases the likelihood of occurrence near the D_{50} dose level, giving the dose-response relationship a characteristic sigmoid shape. Note that when $D_k = D_{50,k}$, then $D_k/D_{50,k} = 1$, $H_k = ln(2)$, and $r_k = 0.5$, as it should since the dose received was the D_{50} dose.

6.2 Stochastic Health Effects Models

The stochastic health effects models calculate individual risk of a latent cancer based on early and late doses to individuals, and the expected number of latent cancers based on early and late population doses. This is different than the early health effects model, which calculates the expected number of effects from the individual risk rather than population dose.

The stochastic health effects models are based on the lifetime organ doses. As discussed in Section 3, the lifetime organ dose is the absorbed dose weighted by the RBE for the type of radiation. These weightings are contained within the dose coefficients and are not part of the health effect calculations. (Note that because the absorbed dose is weighted by RBEs and not radiation weighting factors, the doses are not truly in units of Sieverts. However, since radiation weighting factors are based on RBEs, they are very closely related.) Two of the stochastic dose-response models are based on annual doses, which are the lifetime doses split into annual periods.

The user tells MACCS which organ dose to use for each health effect by specifying the name of the organ dose (e.g., "L-STOMACH") in the parameter $ORGNAM_k$ of health effect k. For cancers, the user should use the organ doses that begin with an "L-" as these are the lifetime organ doses calculated specifically for stochastic health effects. To obtain valid summations for the cancer total, users should make sure risk coefficients account for all cancer types, including cancers in tissues not explicitly modeled in MACCS. Note that the user can specify a risk coefficient for every organ dose, including "L-REMAINDER." "REMAINDER" is a special category commonly given in the DCF files that is treated like any other organ and refers to the remaining organs and tissues that are not explicitly captured by the other organs in the DCF file. The user should also make sure not to double count cancer risk. More specifically, the user should not include a cancer risk coefficient for the effective dose to the whole body (e.g., "L-ICRP60ED") if that cancer risk is already accounted for within a risk coefficient for an organ dose. The "ICRP60ED" is another special category commonly given in the DCF files that is treated like any other organ, even though it is not an organ. "ICRP60ED" provides a set of dose coefficients to calculate the effective dose to the whole body. "ICRP60ED" can be used to calculate cancer incidence and cancer fatalities if the user has risk coefficients, although this is not the recommended approach since MACCS can calculate cancers in a more detailed way for each organ.

For both the individual dose and the population dose, the early and late doses may not be simply added together because of the dose and dose rate effectiveness factor. This is discussed in more detail in the LNT dose-response model and in the other dose-response options.

Individuals in the early phase are grouped into cohorts that receive different amounts of early dose. The formula to calculate the early lifetime dose D_k^E of an individual in a given cohort and spatial element that induces health effect k is shown in Equation (3-8). Note that even though the inhalation exposures that occur during the early phase have a commitment period that may extend beyond the early phase, the full commitment period is accounted for as part of the early dose D_k^E.

In the intermediate and long-term phases, MACCS treats all individuals in a spatial element the same and receive the same late dose D_k^L. The late dose D_k^L to an individual that induces health effect k are the doses from groundshine and resuspension inhalation from the intermediate and long-term phases, as calculated in Equation (3-17).

The formula to calculate early lifetime population dose $D_k^{E,POP}$ for a given cohort and the late lifetime population dose $D_k^{L,POP}$ are Equations (3-58) and (3-59), respectively. In addition to the doses received by individual residents, the late population dose $D_k^{L,POP}$ includes ingestion and decontamination work doses.

Three dose-response models and a total of four dose-response relationships are available in MACCS to calculate cancer incidence and fatalities. The four dose-response relationships are the following:

- Linear, no threshold (LNT),
- Linear quadratic,
- Annual threshold, and
- Piecewise linear.

Users can select the LNT model, annual-threshold model, or the piecewise-linear model by giving the parameter DOSMOD a value of “LNT,” “AT,” or “PL,” respectively. LNT and linear-quadratic relationships are similar and share the same MACCS dose-response model titled “LNT.” To use the LNT dose-response relationship, the acute threshold parameter ACTHRE must be set to a value of zero. To select the linear-quadratic dose-response relationship, the user gives DOSMOD a value of “LNT” and gives ACTHRE a non-zero value.

Figure 6-1 illustrates a comparison of the four dose-response relationships. The figure is a simplified representation because the risk of a cancer effect is generally based on an organ dose chosen by the user and not the effective dose in a year. Therefore, the figure is for illustrative purposes to show the general tendency of the dose-response models compared to each other. The actual dose-response models are discussed in more detail below.

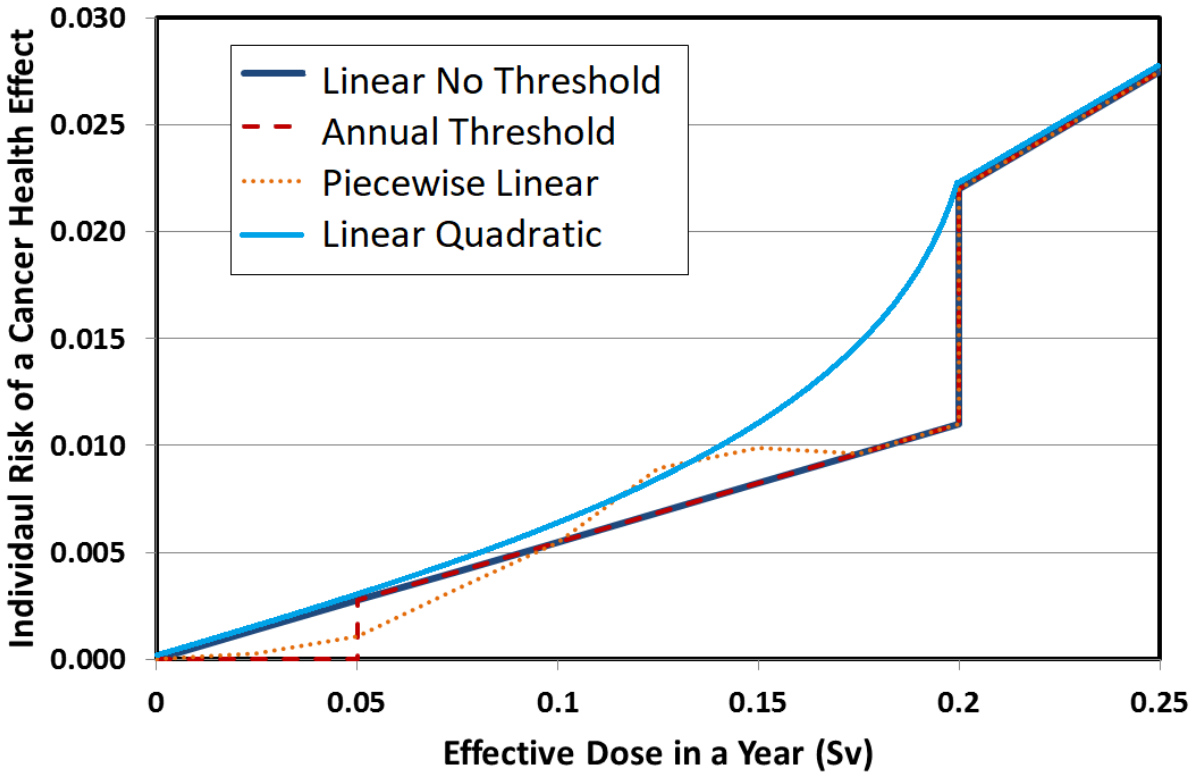

Figure 6-1 The Four Dose-Response Options in MACCS for Estimating Cancer Health Effects

The LNT and the linear-quadratic dose-response relationships are based directly on the lifetime doses. The annual-threshold and piecewise-linear dose-response relationships are based on annual doses. Annual doses are the same as the lifetime dose, except the annual doses are discretized into annual periods.

6.2.1 Linear No Threshold Dose Response

In the LNT dose-response hypothesis, the relationship between dose and health effects is linear, and there is no dose threshold below which there is zero risk. However, the MACCS LNT formula divides the doses that fall below a dose threshold by a dose and dose-rate effectiveness factor. This causes a discontinuity in cancer risk and a change in slope at the threshold dose. Figure 6-1 shows the LNT dose response with a dose and dose-rate effectiveness factor of 2.0 and a corresponding dose threshold of 0.2 Sv (20 rem). Because risk estimates are derived from relatively high dose and dose-rate data, the dose and dose-rate effectiveness factor provides a way to account for the understanding that low doses are disproportionally less likely to induce health effects. As such, the MACCS LNT formula is only a purely linear dose-response relationship when the dose and dose-rate effectiveness factor is equal to one or the dose threshold for DDREF is set to zero.

In the LNT dose-response option, the risk r_k^E of health effect k to an individual in a given cohort and spatial element from early doses has the following dose-response relationship:

$$r_k^E = f_k \cdot RC_k \cdot D_k^E \cdot I_k \qquad \textbf{(6-5)}$$

Where

$$I_k = \begin{cases} 1 & D_k^E \geq D_\alpha \\ \dfrac{1}{\alpha_k} & D_k^E < D_\alpha \end{cases} \qquad \textbf{(6-6)}$$

And where

- f_k is the fraction of the population that is susceptible to the risk of health effect *k*,
- RC_k is the lifetime risk coefficient (*1/Sv*) of health effect *k*, given by the parameter CIRISK$_k$ for cancer incidence and CFRISK$_k$ for cancer fatalities,
- D_k^E is the early dose (*Sv*) portion of the lifetime dose received by an individual in a given cohort and spatial element that induces health effect *k*, as shown in Equation (3-8),
- I_k is a function (dimensionless) that determines when to apply the dose and dose-rate effectiveness factor α for a given cohort and spatial element,
- α_k is the dose and dose-rate effectiveness factor (dimensionless) for health effect *k*, given by the parameter DDREFA$_k$, and
- D_α is the dose threshold (*Sv*) of the dose and dose-rate effectiveness factor, given by the parameter DDTHRE.

The function I_k applies the dose and dose-rate effectiveness factor α to the early dose D_k^E when the early dose is less than the threshold dose D_α. The early phase risk r_k^E does not explicitly consider the dose and dose-rate effectiveness factor for low dose rates.

The risk r_k^L of latent health effect *k* from late doses has the following dose-response relationship:

$$r_k^L = f_k \cdot RC_k \cdot D_k^L \cdot \frac{1}{\alpha_k} \qquad \textbf{(6-7)}$$

Where

- D_k^L is the late dose (*Sv*) portion of the lifetime dose received by an individual in a given spatial element that induces health effect *k*, as given in Equation (3-17), and
- f_k, RC_k, and α_k are the same as before.

Because doses after the early phase are assumed to stay below the threshold, the dose and dose-rate effectiveness factor α always applies in Equation (6-7).

In the LNT dose-response option, the number of stochastic health effects in the early phase N_k^E and in the intermediate and long-term phases N_k^L for a given cohort and spatial element follow the same structure as the individual risk, except they are based on the population dose instead of the individual dose:

$$N_k^E = f_k \cdot RC_k \cdot D_k^{E,POP} \cdot I_k \tag{6-8}$$

and

$$N_k^L = f_k \cdot RC_k \cdot D_k^{L,POP} \cdot \frac{1}{\alpha_k} \tag{6-9}$$

Where

- $D_k^{E,POP}$ is the early lifetime population dose (*person-Sv*) that induces latent health effect k in each cohort and spatial element, as given in Equation (3-58)
- $D_k^{L,POP}$ the late lifetime population dose (*person-Sv*) that induces latent health effect k in each spatial element, as given in Equation (3-59), and
- f_k, RC_k, α_k, and I_k are previously defined.

6.2.2 Linear-Quadratic Dose Response

A second dose-response option in MACCS is the linear-quadratic dose-response relationship. The linear-quadratic option assumes that individual risk from early doses increases quadratically with dose at low doses and linearly with dose at high doses. For late doses, the linear-quadratic option has a linear dose-response relationship and the quadratic portion is neglected (i.e., the linear-quadratic option assumes the late doses are low enough that they do not reach the quadratic portion of the low dose region).

The linear-quadratic option uses almost the same model as LNT. The difference is that for the linear-quadratic option, the special function for the low dose region I_k contains a quadratic term (that is set to zero in the LNT option), and the variables of this function are defined with different terms. When using the linear-quadratic option, the function I_k^{LQ} is used in place of I_k in Equations (6-5) and (6-8) and is as follows:

$$I_k^{LQ} = \begin{cases} 1 & D_k^E \geq D_\alpha \\ \dfrac{1}{\alpha_k} + \beta_k \cdot D_k^E & D_k^E < D_\alpha \end{cases} \tag{6-10}$$

Where

- I_k^{LQ} is a function (dimensionless) that separates the quadratic relationship at low doses from the linear relationship at high doses,

- $\frac{1}{\alpha_k}$ is the linear multiplication factor (dimensionless) in the low dose region, given by the parameter DOSEFA$_k$,

- β_k is the quadratic factor (dimensionless) in the low dose region, given by the parameter DOSEFB$_k$, and

- D_α is the dose threshold (*Sv*) separating the low dose region from the high dose region, given by the parameter ACTHRE.

When the quadratic factor β_k is set to zero, the linear-quadratic option and the LNT option are identical. Note that while the terms are defined differently, DOSEFA$_k$ corresponds to the inverse of the dose and dose-rate effectiveness factor DDREFA$_k$, and ACTHRE corresponds to the dose threshold (*Sv*) of the dose and dose-rate effectiveness factor DDTHRE.

When using the linear-quadratic option, either DDTHRE needs to be set to zero and / or DDREFA$_k$ needs to be set to one so that I_k does not apply. When not using the linear-quadratic option, ACTHRE should be set to zero so that the function I_k^{LQ} does not apply.

6.2.3 Annual-Threshold Dose Response

The third dose-response option is the annual-threshold model. Instead of directly using the lifetime dose, this model evaluates annual doses. As discussed in Section 3, an annual dose D_{ky} in year *y* refers to the year that the dose is received, not the year that intake occurs. MACCS divides the lifetime dose from each intake period and assigns them to different years. For instance, direct inhalation during the early phase and resuspension inhalation in year 3 can both contribute to a dose in year 7. MACCS sums the contributions from the different intake periods to find the annual internal dose in year *y*, which is then summed with the external annual dose in year *y* to obtain the annual doses from all pathways.

The dose-response threshold is specified in terms of an annual effective dose (*Sv*). The user can specify one or more annual effective dose threshold values (*Sv*) in the parameter DTHANN, up to one for each year of the exposure period. (The value specified for the last year is used for all subsequent years. When a single value is listed, it applies to every year of the exposure period.) In the years that the annual effective dose is less than the annual threshold, MACCS excludes the corresponding annual dose contribution from the health effect calculation; in the years that the predicted annual effective dose exceeds the annual threshold, the dose contribution to health consequences is the same as the LNT model. Figure 6-1 illustrates a case using an annual threshold of 0.05 Sv (5 rem). Annual dose contributions are then summed over all years to calculate health effects.

The user may optionally specify a lifetime dose threshold (*Sv*) in the parameter DTHLIF. When using a lifetime threshold, MACCS excludes dose contributions only when the lifetime effective dose is below the lifetime threshold. If either the annual effective doses or the lifetime effective dose exceeds their respective thresholds, the annual dose contributions have the same effect as they do in the LNT model.

In the MACCS annual-threshold dose response, the truncated risk r_k^M of health effect k for an average individual in a given cohort and spatial element is the following:

$$r_k^M = f_k \cdot RC_k \cdot D_k^M \tag{6-11}$$

Where

- D_k^M is the modified lifetime dose that induces health effect k in individuals for a given cohort and spatial element, and

- f_k and RC_k are previously defined.

The modified lifetime dose D_k^M is like the lifetime dose, except that the dose contribution from years that do not exceed the annual threshold are removed. Also, as calculated in the MACCS annual-threshold model, the dose and dose rate effectiveness factor α is already accounted for inside the value of the modified lifetime dose D_k^M, which is why it does not appear in Equation (6-11).

The modified lifetime dose D_k^M is based on the early lifetime dose D_k^E and the late lifetime dose D_k^L that have been split into annual periods. These are called the early annual doses D_{ky}^E and the late annual doses D_{ky}^L. Note that the sum of the early and late annual doses is simply the lifetime dose, $D_k = \sum_y \left(D_{ky}^E + D_{ky}^L\right)$. Also note that "early" and "late" refer to when exposure occurs and not to when the dose occurs. Because intakes from internal pathways occur over a commitment period, inhalation in the early phase can cause doses after the first year, as can late intakes.

The modified lifetime dose D_k^M that induces latent health effect k in a given cohort and spatial element is calculated in the following way:

$$D_k^M = \sum_y D_{ky}^M \cdot I_y \tag{6-12}$$

Where

$$I_y = \begin{cases} 0 & D_y^{eff} < D_T \\ 1 & D_y^{eff} \geq D_T \end{cases} \tag{6-13}$$

And where

- D_{ky}^M is the annual dose in year y that may induce latent health effect k in a given cohort and spatial element, and is weighted by the dose and dose-rate effectiveness factor α, as discussed below,

- I_y is an indicator function (dimensionless) for a given cohort and spatial element that determines whether to truncate the dose from year y,

- D_y^{eff} is the annual effective dose (*Sv*) in year *y* for a given cohort and spatial element, and

- D_T is the annual dose truncation (*Sv*), given by the parameter DTHANN$_y$.

MACCS calculates the annual effective dose D_y^{eff} in year *y*, where year *y* refers to the year that the dose is received. The indicator function I_y is based on the effective dose D_y^{eff} from year *y* in a given cohort and spatial element. When D_y^{eff} is less than the annual dose threshold D_T, I_y returns a value of zero. This eliminates the dose contribution from year *y*. The annual doses D_{ky}^M from years that exceed the annual threshold contribute to the truncated risk r_k^M.

The annual doses weighted by the dose and dose-rate effectiveness factor D_{ky}^M is calculated in the following way:

$$D_{ky}^M = D_{ky}^E \cdot I_k + D_{ky}^L \cdot \frac{1}{\alpha_k} \tag{6-14}$$

- D_{ky}^E is the annual early dose (*Sv*) during year *y* in a given cohort and spatial element,
- D_{ky}^L is the annual late dose (*Sv*) during year *y* in a spatial element, and
- α_k and I_k are previously defined under Equation (6-5)

MACCS calculates the annual doses D_{ky}^E and D_{ky}^L in year *y*, where year *y* refers to the year that the dose is received. Equation (6-14) follows the same pattern for calculating risk as it does for the LNT model, except it now applies to annual doses. The annual early dose is multiplied by the function I_k, which divides the annual early dose by the dose and dose-rate effectiveness factor α when the early dose is less than the threshold for α. MACCS assumes the annual late doses stay below the threshold, so they are always divided by the dose and dose-rate effectiveness factor α.

Just as with the LNT dose response, the truncated number of stochastic health effects N_k^M follow the same structure as the truncated individual risk r_k^M, except they are based on the population dose instead of the individual dose:

$$N_k^M = f_k \cdot RC_k \cdot D_{ik}^{M,POP} \tag{6-15}$$

Where

- $D_k^{M,POP}$ is the modified lifetime population dose that induces latent health effect *k* in a given cohort and spatial element discussed below, and

- f_k and RC_k are previously defined.

MACCS uses the same set of Equations (6-12) through (6-14) to calculate the modified lifetime population dose $D_k^{M,POP}$ as the individual dose D_k^M. That is, MACCS uses the individual annual effective dose D_y^{eff} to determine when to truncate the population dose, and applies a dose and dose rate effectiveness factor to the early and late doses separately as shown above before summing them together. The difference is that because the population dose includes the food and water ingestion pathways, the individual annual effective dose D_y^{eff} now also includes the dose contributions from food and water ingestion. These additions are calculated by taking the annual population dose for food and water ingestion and weighting them by the resident population in the spatial element, that is DF_y/Pop and DW_y/Pop. These additions make a difference when they increase D_y^{eff} beyond the annual threshold D_T.

The decontamination worker dose DWD_{yk} is also part of the overall population dose D_k^{POP}. However, MACCS does not add their contribution to the individual annual effective dose D_y^{eff} as done for the ingestion pathways. Instead, MACCS evaluates whether the effective dose to individual workers exceeds the annual threshold D_T separate from the resident individuals. When it does, decontamination worker dose DWD_{yk} contributes to the modified population dose $D_k^{M,POP}$. The individual work dose is the population worker dose weighted by the number of workers (e.g., $DWD_{yk}^{NF}/NFWorkers$) and is done separate for farm and non-farm workers.

6.2.4 Piecewise-Linear Dose Response

The fourth dose-response option is called the piecewise-linear model. The piecewise-linear model uses annual doses like the annual-threshold model and calculates health risks in the same fashion. In this model, the user can construct a series of line segments that define the functional dependence of annual dose on health effects, as illustrated in Figure 6-1. This model can be used to approximate a dose threshold, to create a sublinear dose-response model, or to create a supra-linear dose-response model. It cannot be used to construct a hormesis model because MACCS does not allow beneficial health effects (negative risk) from radiation exposure.

To define the piecewise-linear dose-response relationship, MACCS starts with the LNT dose-response relationship as the base and then requires the user to define a set of risk multipliers at a set of dose levels. These define the vertices of the piecewise-linear function, which MACCS uses to construct the full continuous piecewise-linear function. For each vertex point *j* of the piecewise-linear model, the user enters the dose level into the parameter $PWLDOS_j$ and the risk multiplier into the parameter $PWLFAC_j$. PWLFAC values greater than one have a risk greater than the LNT dose response at this dose level, and values less than one have less risk than LNT. The user does not define the first corner point, which is zero, and the last value of PWLFAC must be one. Doses greater than the last dose level follow the LNT dose-response model.

Figure 6-1 illustrates a piecewise-linear model that is sublinear below 0.1 Sv (10 rem) and supra-linear between 0.1 Sv and 0.175 Sv (17.5 rem). In this example, the last dose level of the piecewise-linear function is 0.175 Sv. Above 0.175 Sv, the piecewise-linear model is identical to the LNT model.

6.3 Health Effect Model Outputs

MACCS reports five output categories related to health effect model results. Some of the outputs are results only from the early phase (generated by the EARLY module), while other outputs can be results from all accident phases (generated from both the EARLY and CHRONC modules). Table 6-1 gives a breakdown of each output category:

Table 6-1 Health Effect Output Category Breakdown by Module

Result Type	EARLY	CHRONC	Cohort-specific Results	Method of Combining Cohorts
Type 1: Health Effect Cases	X	X	Yes	Sum
Type 2: Early Fatality Distance	X		Yes	Weighted average
Type 4: Average Individual Risk	X	X	Yes	Weighted average
Type 7: Centerline Risk	X	X	Yes	Weighted average
Type 8: Population-weighted Individual Risk (i.e., Safety Goal Risk)	X	X	Yes	Weighted average

When an output comes from both the EARLY module and the CHRONC module (i.e., Type 1, 4, 7, and 8), the overall results from the two modules are summed together. If the CHRONC module is not run, MACCS only reports the early phase contribution in the health effect outputs. This provides incomplete values if the intermediate and long-term phases are relevant to the analysis.

Additionally, Type 4, 7 and 8 do not include health effect contributions from indirect dose pathways, those being ingestion doses or decontamination worker doses. Because of additional transport of food and water, ingestion doses do not necessarily occur in the spatial element where deposition occurs, and MACCS does not attempt to model the actual location. Thus, the reported values of individual cancer risk are based on a partial set of dose contributions. Decontamination workers are likely to be a different cohort than residents and thus these doses are not attributed to these risk outputs either. As such, these outputs still provide incomplete values if these pathways are relevant to the analysis. Only Type 1 ("Health Effect Cases") consider contributions from all MACCS pathways, making "Health Effect Cases" a more complete measure compared to individual risk measures. Even though the recipients of the indirect doses may not live in this location, the Type 1 output attributes ingestion and decontamination worker doses to the spatial element where deposition occurred.

The output results are broken down into overall results and cohort-specific results. The early phase contribution to the overall results is a combination of the early cohort results, either a summation or a weighted average. MACCS sums the Type 1 cohort results, as the Type 1 output is a type of collective result. The other four types (i.e., Type 2, 4, 7, and 8) combine the early cohorts using a weighted average based on the population fraction of the cohort. The mathematical expressions for calculating the overall results depend on the cohort model selected by the user and is discussed in Section 1.5.

Except for Type 2, each output category reports results for each user-specified health effect. The user defines the names of the health effects in the parameter EINAME for early injuries and

ACNAME for cancers. The health effect names are then displayed within the output blocks when requested, as shown in Table 6-2.

Table 6-2 Health Effect Outputs

Output Name	Description
ERL FAT/TOTAL	Number (or risk) of early fatalities
ERL INJ/THYROIDITIS	Number (or risk) of “THYROIDITIS” injuries
ERL INJ/PNEUMONITIS	Number (or risk) of “PNEUMONITIS” injuries
…	…
CAN FAT/THYROID	Number (or risk) of “THYROID” cancer fatalities
CAN FAT/BREAST	Number (or risk) of “BREAST” cancer fatalities
CAN FAT/REMAINDER	Number (or risk) of “REMAINDER” cancer fatalities
CAN FAT/TOTAL[a]	Sum of cancer fatalities (or fatal cancer risk)
…	…
CAN INJ/THYROID	Number (or risk) of “THYROID” cancer incidence
CAN INJ/BREAST	Number (or risk) of “BREAST” cancer incidence
CAN INJ/REMAINDER	Number (or risk) of “REMAINDER” cancer incidence
CAN INJ/TOTAL	Sum of cancer incidence (or cancer risk)

[a] Not available for “Average Individual Risk” outputs.

For early fatality results, “TOTAL” is based on an aggregated hazard function. This is discussed in more detail in Section 6.1. MACCS does not report an early injury total and does not calculate individual types of early fatalities.

For cancer results, “TOTAL” is a summation of the calculated number of health effects. To obtain proper summations for “TOTAL” cancer results, it is necessary to specify a complete list of cancer types, along with their risk coefficients and other pertinent information. Users should also ensure not to double count cancer risk using the “L-ICRP60ED” dose, which is the effective dose to the whole body. Including risk coefficients for the “L-ICRP60ED” dose adds cancer risk from the whole body to the “TOTAL,” making the total invalid if the risk of those cancers is already explicitly accounted for within the individual organ doses.

Type 1: Health Effect Cases

The Type 1 output is the expected cases of a user-specified health effect in a region of interest. The user specifies the region of interest by specifying two radial intervals that define the range of the region. The health effects can be either early health effects or stochastic health effects. The Type 1 output considers health effects from early doses generated by the EARLY module as well as late doses generated by the CHRONC module when the CHRONC module is run. This includes stochastic health effects from ingestion and decontamination worker doses.

Early health effects only depend on the early phase results. MACCS calculates the expected cases of a given early injury in a given cohort using Equation (6-1). Likewise, MACCS also calculates the expected cases of total early fatalities in a given cohort using Equation (6-1). MACCS does not calculate total early fatalities as a sum of different types of early fatalities, as this could cause a double counting of early fatalities if an individual receives a lethal dose to two or more organs.

Stochastic health effects depend on both early doses and late doses. If the CHRONC module is not run, the Type 1 output only displays results from the early phase doses (i.e., EARLY module). This provides incomplete values if the intermediate and long-term phases are relevant to the analysis.

When using the LNT or linear-quadratic option, MACCS calculates the expected incidence (or fatalities) from a given cancer in a given cohort in the early phase using Equation (6-8), and the expected incidence (or fatalities) from a given cancer in the intermediate and long-term phases using Equation (6-9). When using annual-threshold or piecewise-linear option, MACCS instead uses Equation (6-15).

Table 6-3 Derivations for Expected Number of Health Effects

Health Effect Cases	Early Dose	Late Dose
Number of early injuries	Equation (6-1)	N/A
Number of early fatalities	Equation (6-1)	N/A
Number of cancers or fatalities		
Dose Response: LNT or LQ	Equation (6-8)	Equation (6-9)
Dose Response: AT or PL	Equation (6-15)	

The expected number of a given health effect is a summation of the health effect cases for all cohorts in the early phase and, if applicable, all cases in the intermediate and long-term phases. How MACCS calculates the overall results is discussed in more detail in Section 1.5.

Type 2: Early Fatality Distance

MACCS reports the radius from the site (*km*) that is expected to exceed an early fatality risk level, according to the risk calculation in Equation (6-3). The user specifies the risk level for the output in the parameter RISTHR.

- A risk level of 0.5 corresponds to the distance from the site that early fatalities would occur in 50% of the population.

- A risk level of 0.0 corresponds to the distance from the site that early fatalities are possible. This calculates a distance where early fatalities could occur for the most radiosensitive people in the population, which is when an acute dose exceeds an early fatality dose threshold.

Type 4: Average Individual Risk

The average individual risk is a compass sector-average risk of a user-specified health effect to an individual in a user-specified radial interval. The Type 4 output considers health effects from early doses generated by the EARLY module as well as late doses generated by the CHRONC module when the CHRONC module is run. The Type 4 output does not include health effects from ingestion and decontamination worker doses.

The Type 4 output is obtained by taking the sum of the risk values across all the compass sectors of a single radial interval and dividing it by the number of sectors. This result is the same as the population-weighted risk only when the population distribution is uniform. For most site-specific analyses, population-weighted risk is a more useful result.

Early health effects only depend on the early phase results. In a given spatial element, MACCS calculates the risk r_{ik}^{E} of a given type of early injury for an individual in cohort i using Equation (6-2). Similarly, MACCS calculates the risk r_{ik}^{E} of total early fatality for an individual in cohort i using Equation (6-3).

Cancer (and cancer fatalities) can depend on both early phase results and intermediate and long-term results. In a given spatial element, when using a LNT or linear-quadratic dose-response option, MACCS calculates the early risk contribution r_{ik}^{E} of cancer k for an individual in cohort i using Equation (6-5). MACCS calculates the late risk contribution r_{k}^{L} of cancer k using Equation (6-7). When using an annual-threshold or piecewise-linear dose-response option, MACCS instead uses Equation (6-11). This is summarized in Table 6-4.

Table 6-4 Derivations for Average Individual Risk

Average Individual Risk	Early Dose	Late Dose
Risk of early injuries	Equation (6-2)	N/A
Risk of early fatalities	Equation (6-3)	N/A
Risk of cancer incidence or fatalities		
Dose Response: LNT or LQ	Equation (6-5)	Equation (6-7)
Dose Response: AT or PL	Equation (6-11)	

Type 7: Centerline Risk

Centerline risk is the risk of a user-specified health effect to a phantom individual exposed to air and ground concentrations directly under the plume path. The Type 7 output reports the centerline risk for each radial interval within a region of interest. The user specifies the region of interest by specifying two radial intervals that define the range of the region. The Type 7 output considers health effects from early doses generated by the EARLY module as well as late doses generated by the CHRONC module when the CHRONC module is run. The Type 7 output does not include health effects from ingestion and decontamination worker doses. Result are only available when wind shift is turned off (i.e., IPLUME = 1). The centerline risk is not affected by protective actions.

Just like the Type 4 and 8 outputs, the centerline risk of early health effects is based on the total acute dose from the early phase, and the centerline risk of cancer (and cancer fatalities) is based on the total lifetime dose from all accident phases. In fact, the centerline risk uses the same equations in Table 6-4 with one exception: The centerline risk is based on the centerline dose (i.e., Type 6) rather than the typical dose inputs discussed in these equations. The only differences between these dose values are that the centerline dose does not include an off-centerline correction factor and is not affected by protective actions. Most dose calculations use an off-centerline correction factor to adjust the centerline dose to an average dose for the spatial element. In order to calculate centerline risk, the Type 7 output does not contain this off-centerline correction factor.

Type 8: Population-Weighted Individual Risk (i.e., Safety Goal Risk)

The population-weighted individual risk is the average risk of a user-specified health effect to individuals within a region of interest. The user specifies the region of interest by specifying two radial intervals that define the range of the region. The Type 8 output considers health effects from early doses generated by the EARLY module as well as late doses generated by the CHRONC module when the CHRONC module is run. The Type 8 output does not include health effects from ingestion and decontamination worker doses.

The Type 8 results are also known as the safety goal risk output. For comparison against the NRC safety goals, the outputs of interest are the 1-mile total early fatality risk and the 10-mile total cancer fatality risk metrics.

In a given spatial element, the derivations for the population-weighted risk (Type 8) are the same as they are for the average individual risk (Type 4). This is summarized in Table 6-4. Rather, Type 8 and Type 4 outputs are different in how they compute an average within the region of interest. MACCS obtains results for the Type 8 output by calculating the expected cases of a given health effect in the region of interest and then dividing by the total population in the region.

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